

[54] ROTATIONAL VISCOMETER

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[51] Int. Cl.³ G01N 11/14

[52] U.S. Cl. 73/60

[58] Field of Search 73/54, 59, 60

[56] References Cited

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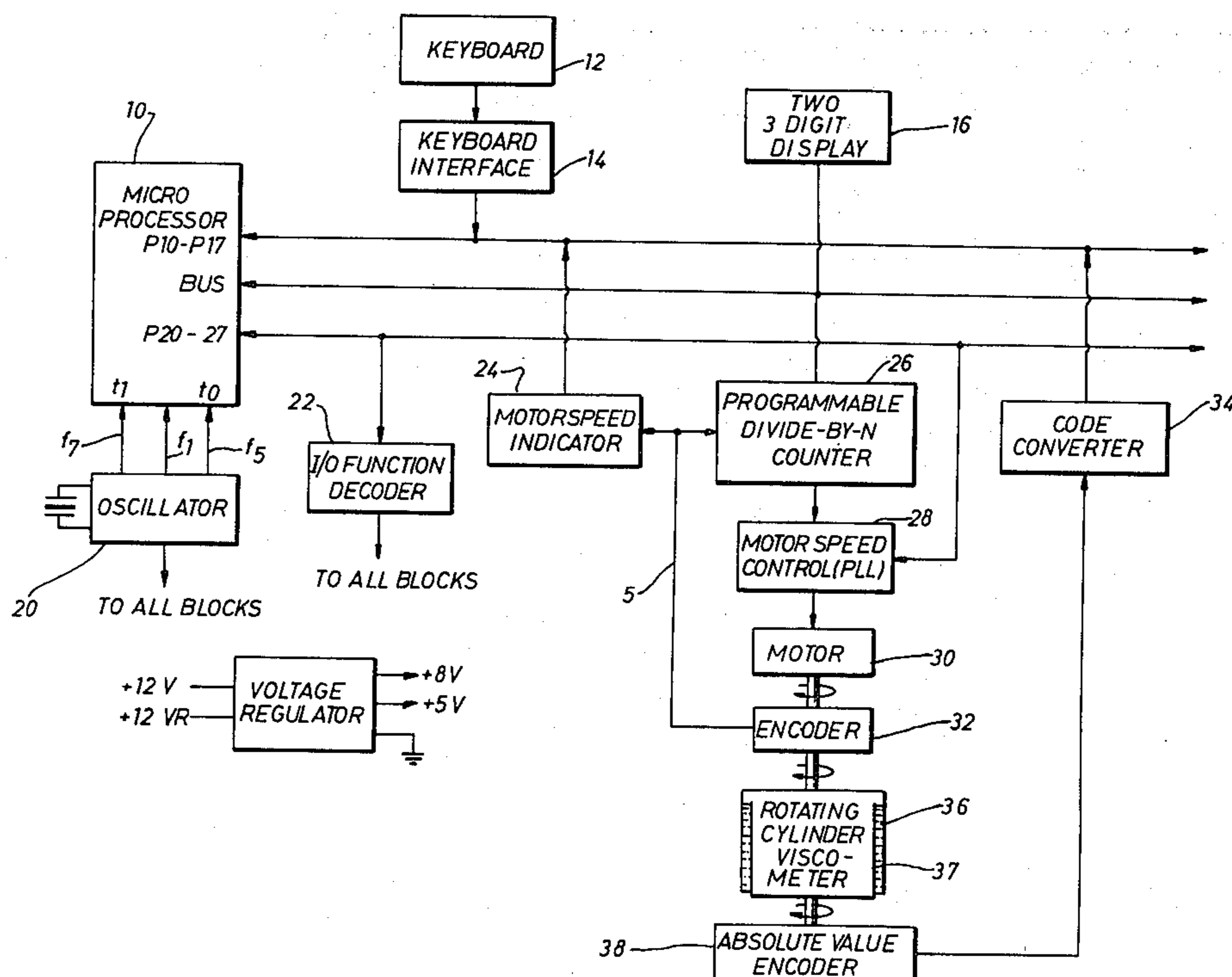
Primary Examiner—James J. Gill

Attorney, Agent, or Firm—John N. Hazelwood; Peggy L. Smith

[57] ABSTRACT

A microprocessor controlled rotating-cylinder viscometer for measuring the shear stress at a given shear rate of a fluid is disclosed. The fluid is contained between a rotatable outer cylinder and a rotatable inner cylinder. The inner cylinder rotates in response to the torque produced by rotation of the outer cylinder in the fluid. The amount of rotation of the inner cylinder is related to the shear stress of the fluid. A fast slewing accurate motor speed control is provided for maintaining rotation of the outer cylinder at the selected shear rates. An absolute value shaft encoder monitors the amount of rotation of the inner cylinder to obtain the shear stress readings. The steady state value of the shear stress is obtained by averaging a predetermined number of measurements taken over a sample interval to obtain a stress reading. Consecutive readings are compared until the difference between readings is less than $\pm 1^\circ$, the current shear stress then taken on the steady state value.

32 Claims, 16 Drawing Figures



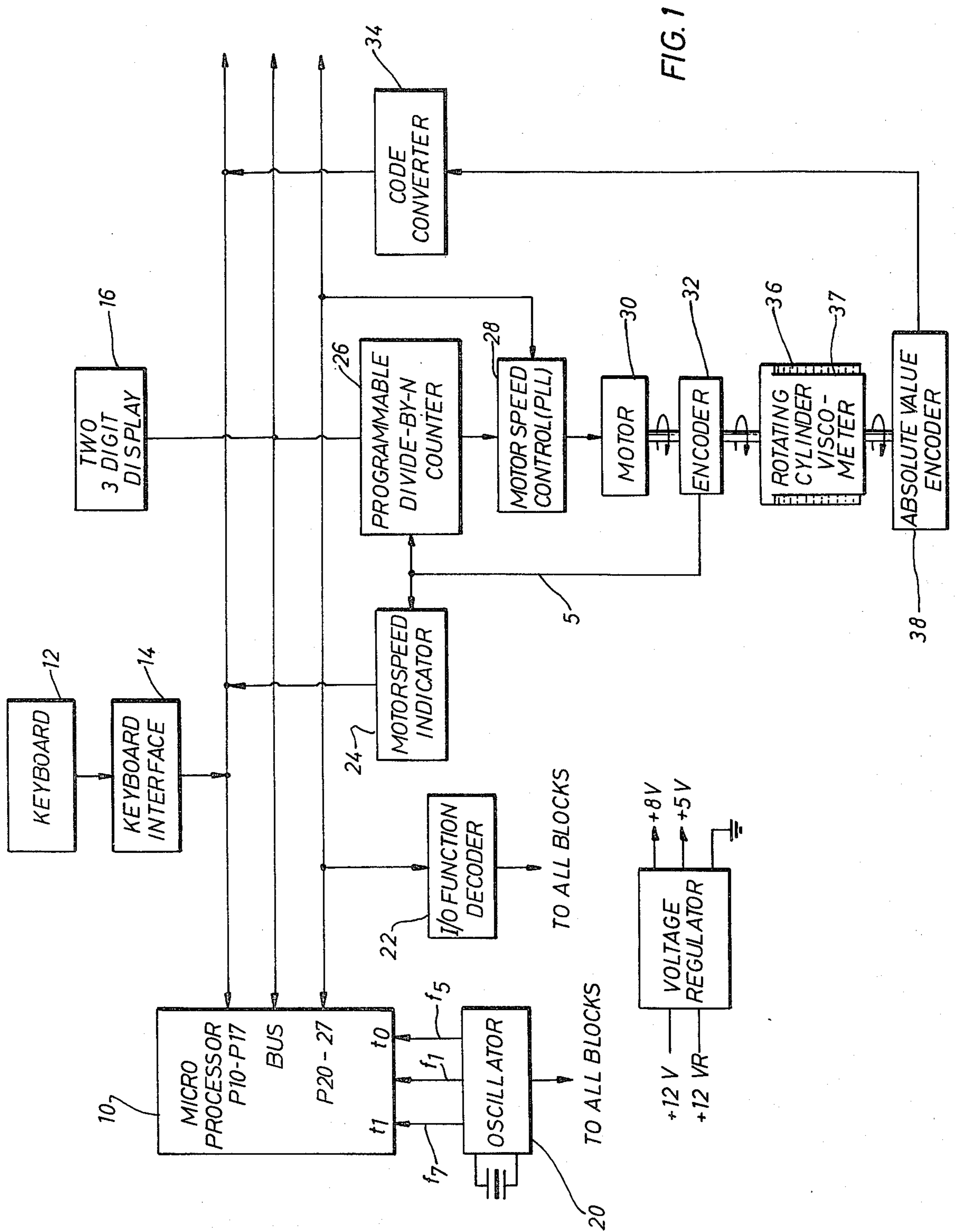


FIG. 1

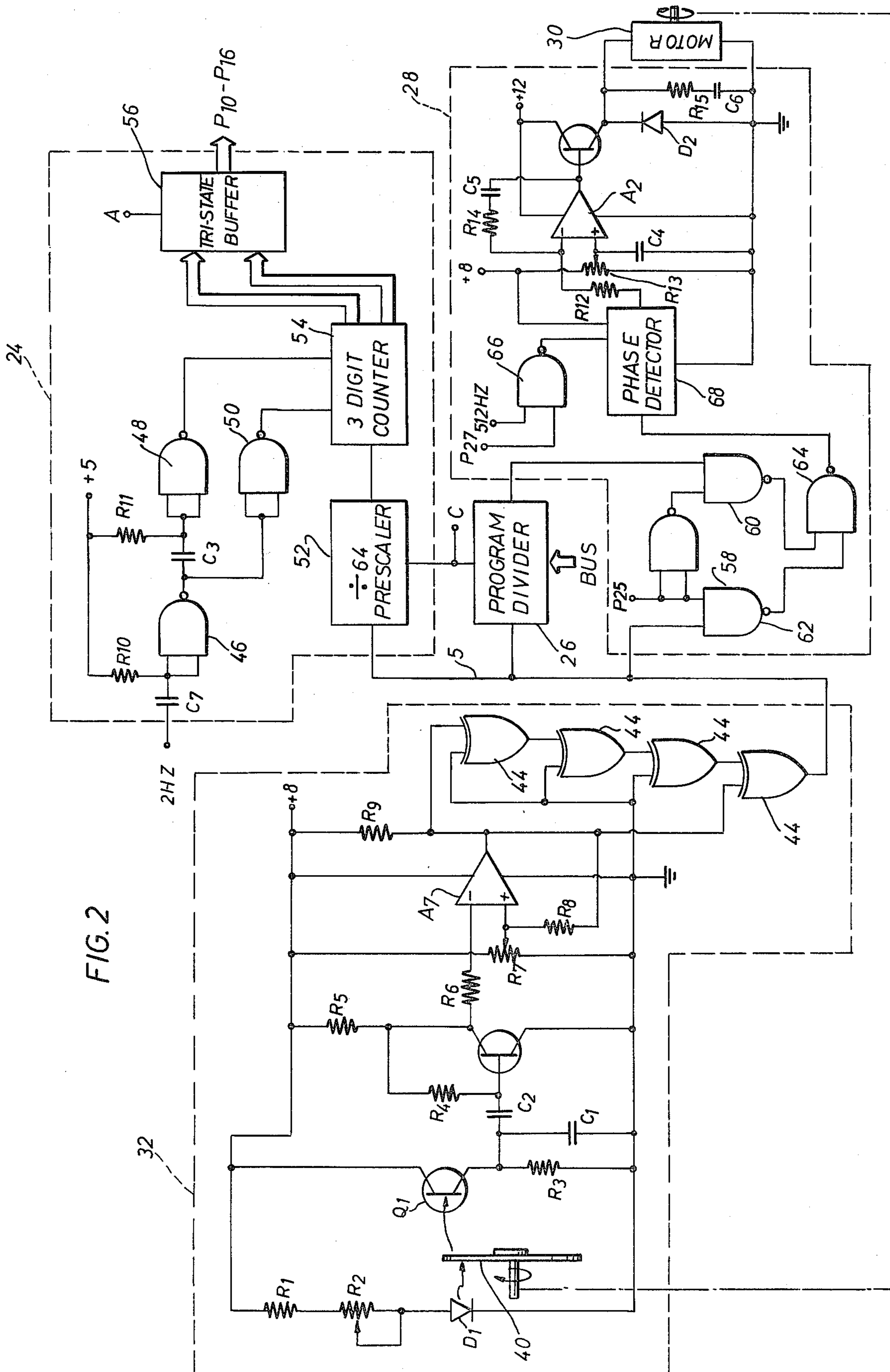


FIG. 2

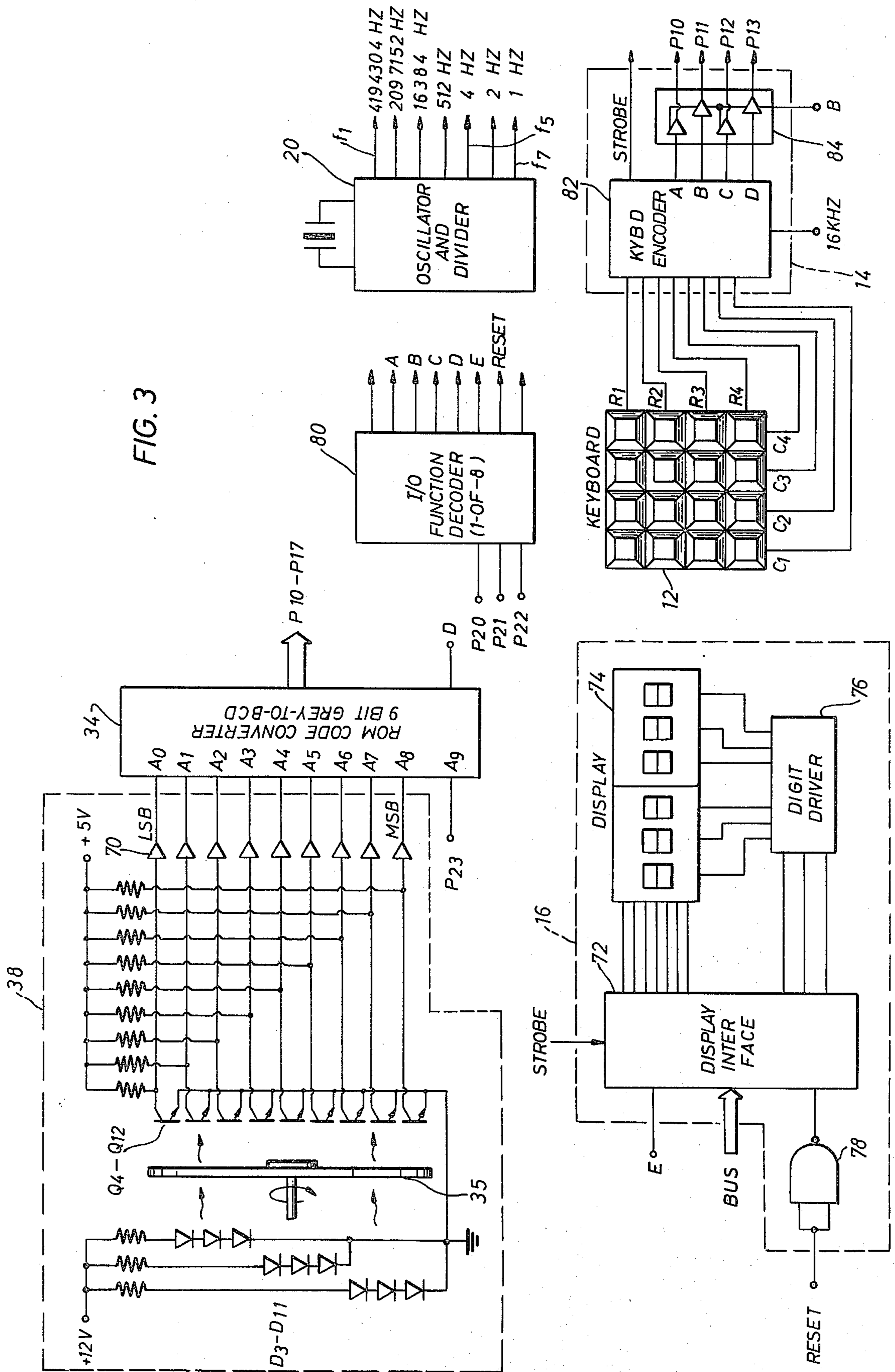


FIG. 4

MEMORY AND I/O ASSIGNMENTS

ROM

| ADDRESS | ALLOCATION |
|---------|------------------------|
| 00-3CF | PROGRAM MEMORY |
| 3D0-3FF | BCD-7SEG. LOOKUP TABLE |
| 400-7FF | PROGRAM MEMORY |

RAM

| ADDRESS | ALLOCATION |
|---------|-------------------------|
| 00-07 | REGISTERS 0 TO 7 |
| 08-17 | 8 LEVEL STACK |
| 18-1A | KEYBOARD DATA |
| 1B-1D | RPM AND TIME DATA |
| 1E-20 | STRESS AND MESSAGE DATA |
| 21-3E | STRESS STORAGE |
| 40-5D | SPEED STORAGE |
| 5E-7F | SCRATCH PAD MEMORY |

P1

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|

P10-13 BCD INPUTS

P14-17 BCD AND DIGIT SELECT INPUTS

P2

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 7 | 6 | 5 | 4 | 3 | 2 | 1 | 0 |
|---|---|---|---|---|---|---|---|

P20-22 CHIP SELECT DECODER ADDRESS

P23-24 CONTROL OUTPUTS

P25 1RPM ACTIVATOR

P27 MOTOR ENABLE ACTIVATOR

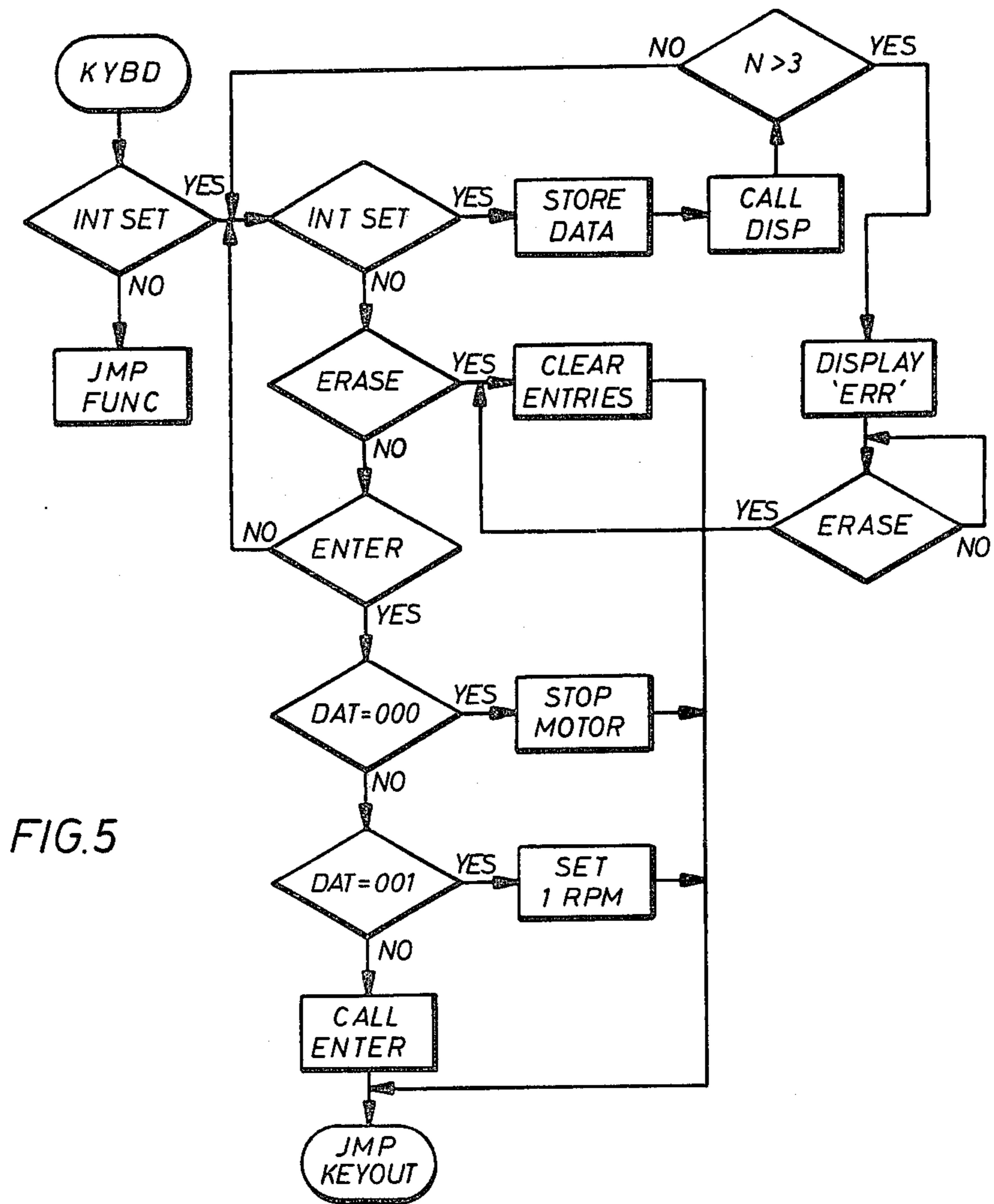


FIG. 5

FIG. 6

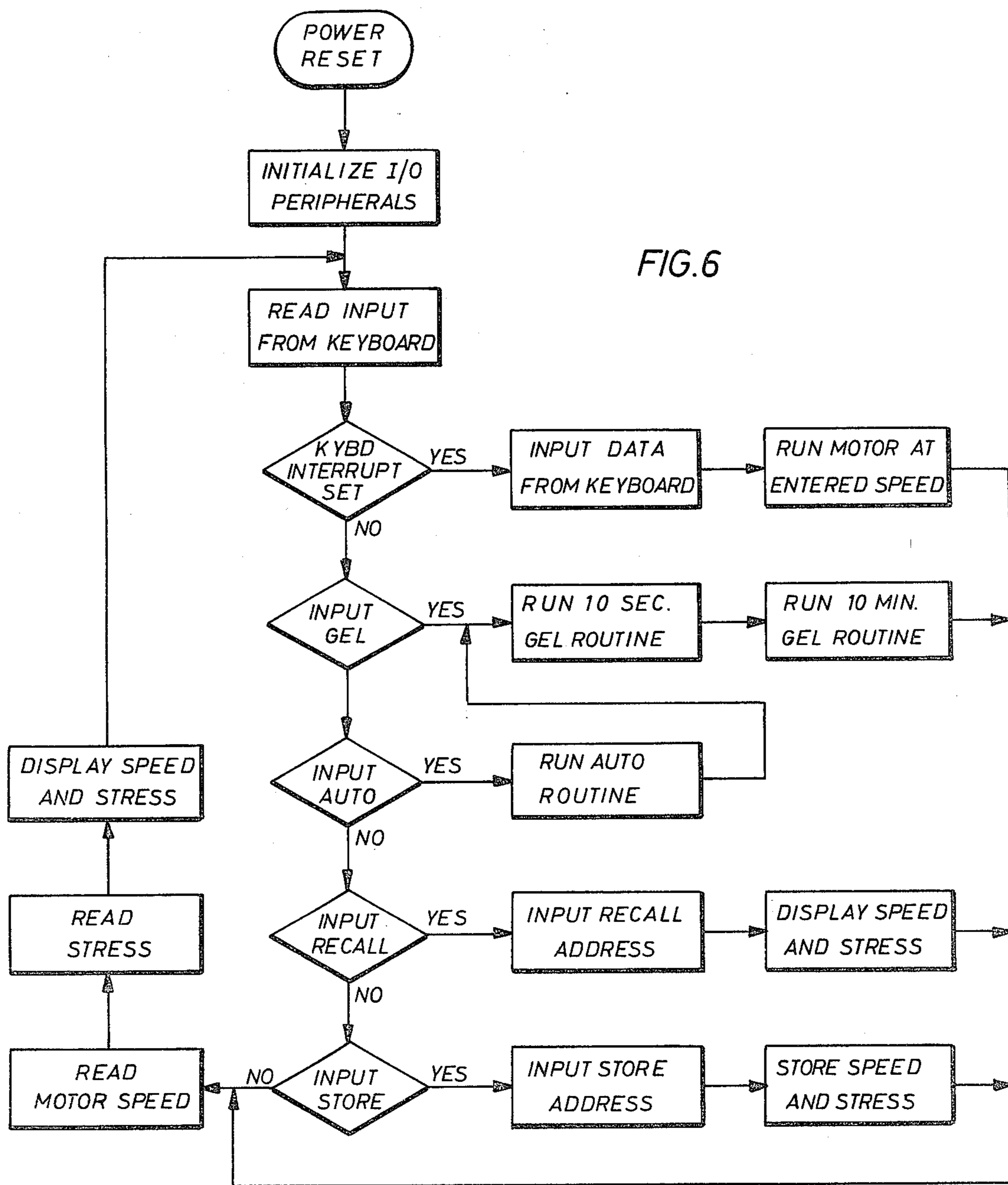


FIG. 7

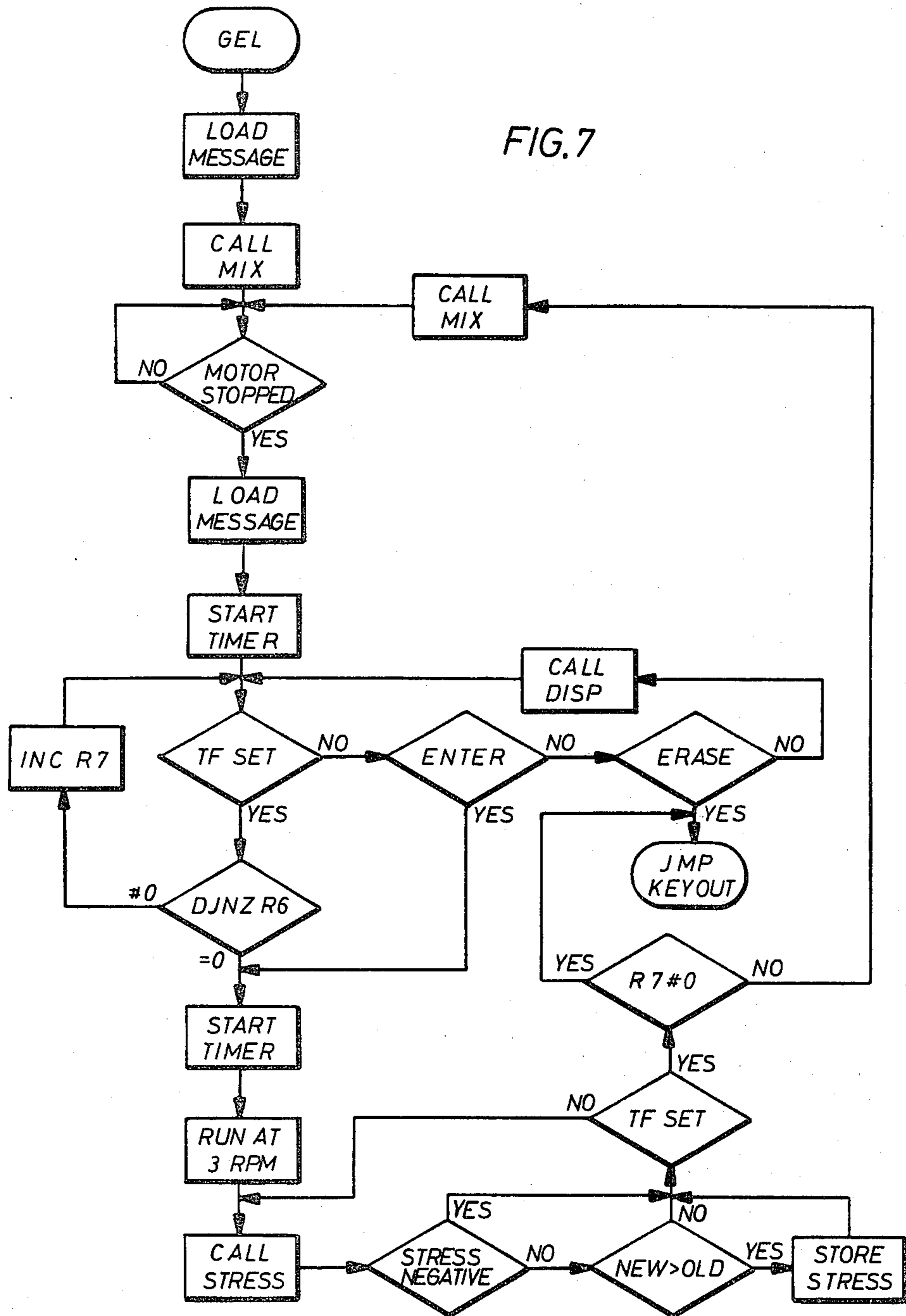
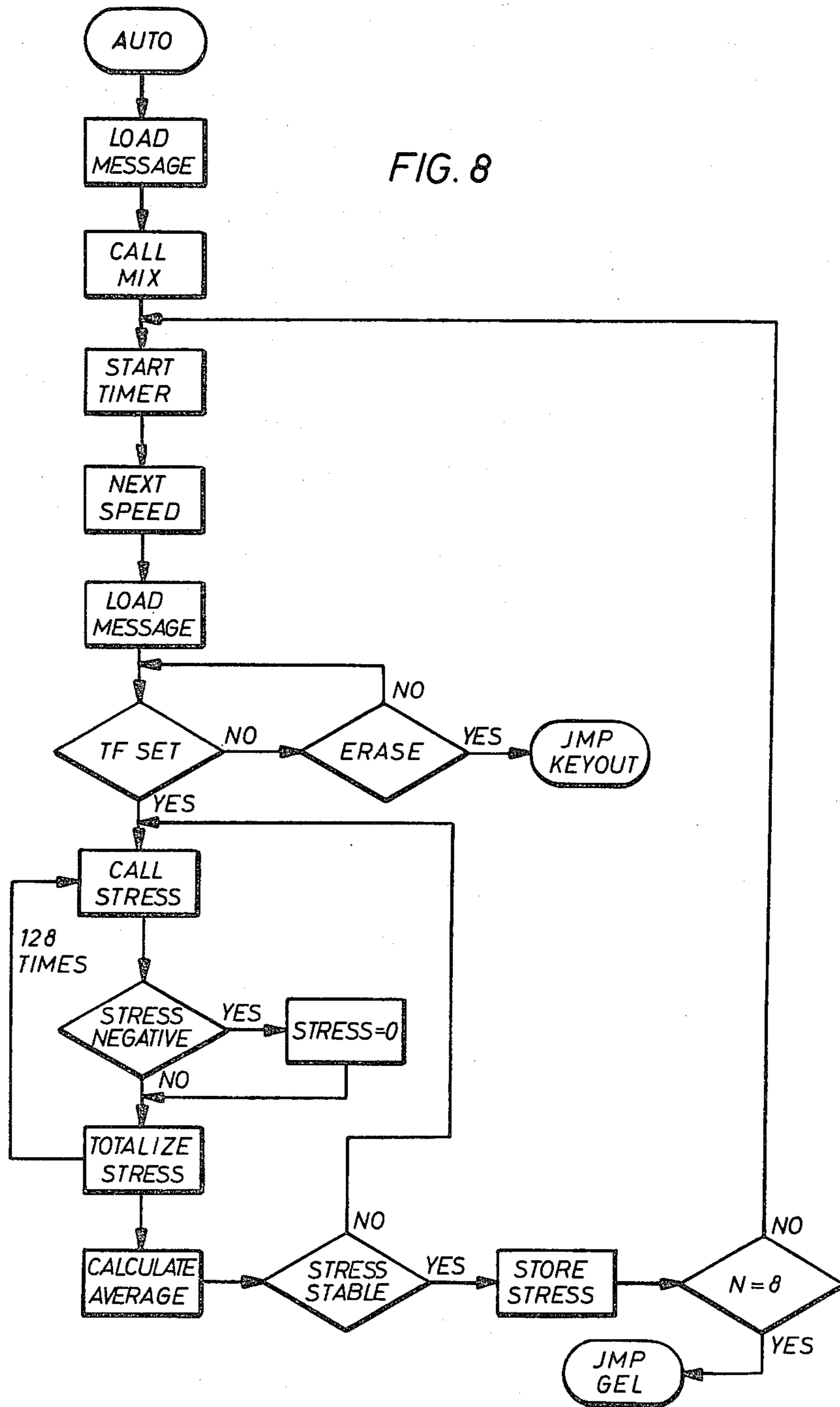


FIG. 8



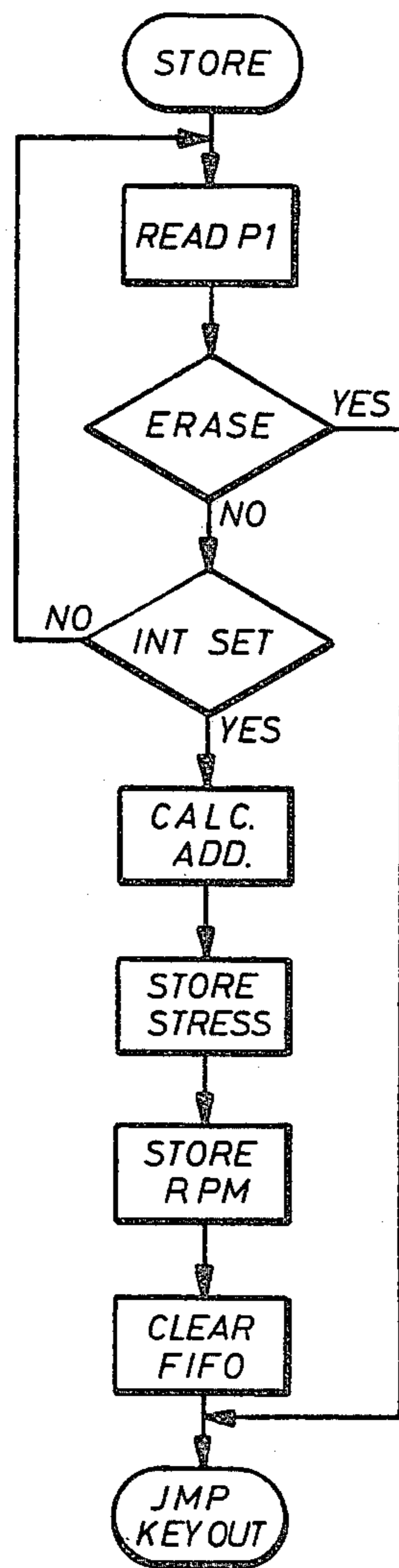


FIG. 9

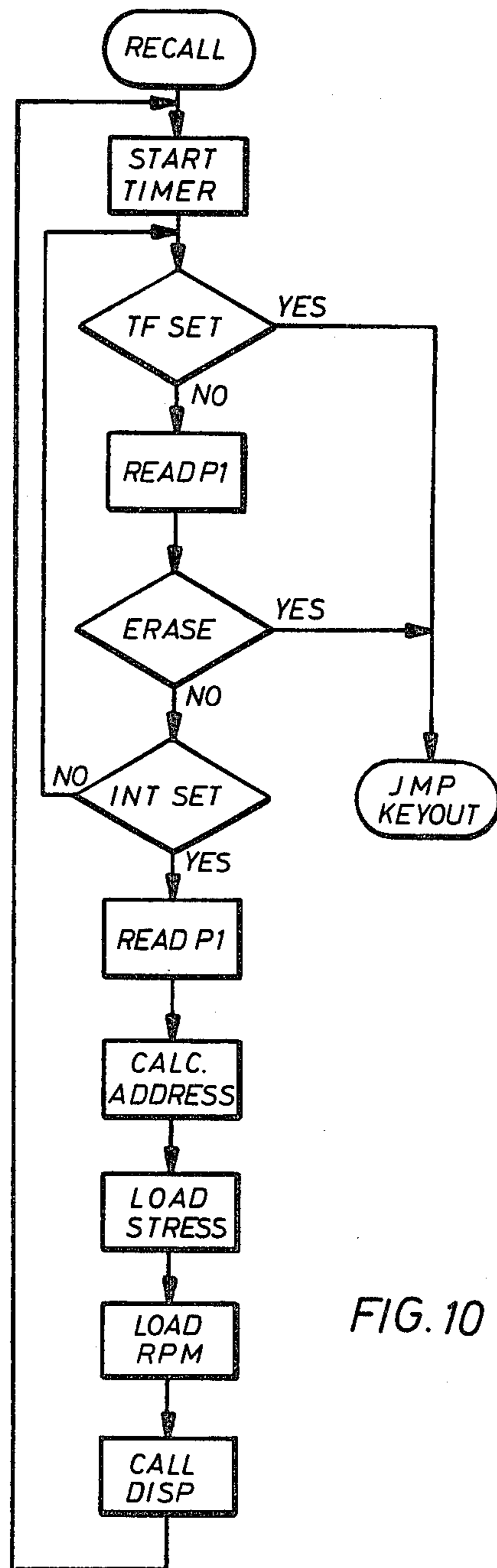


FIG. 10

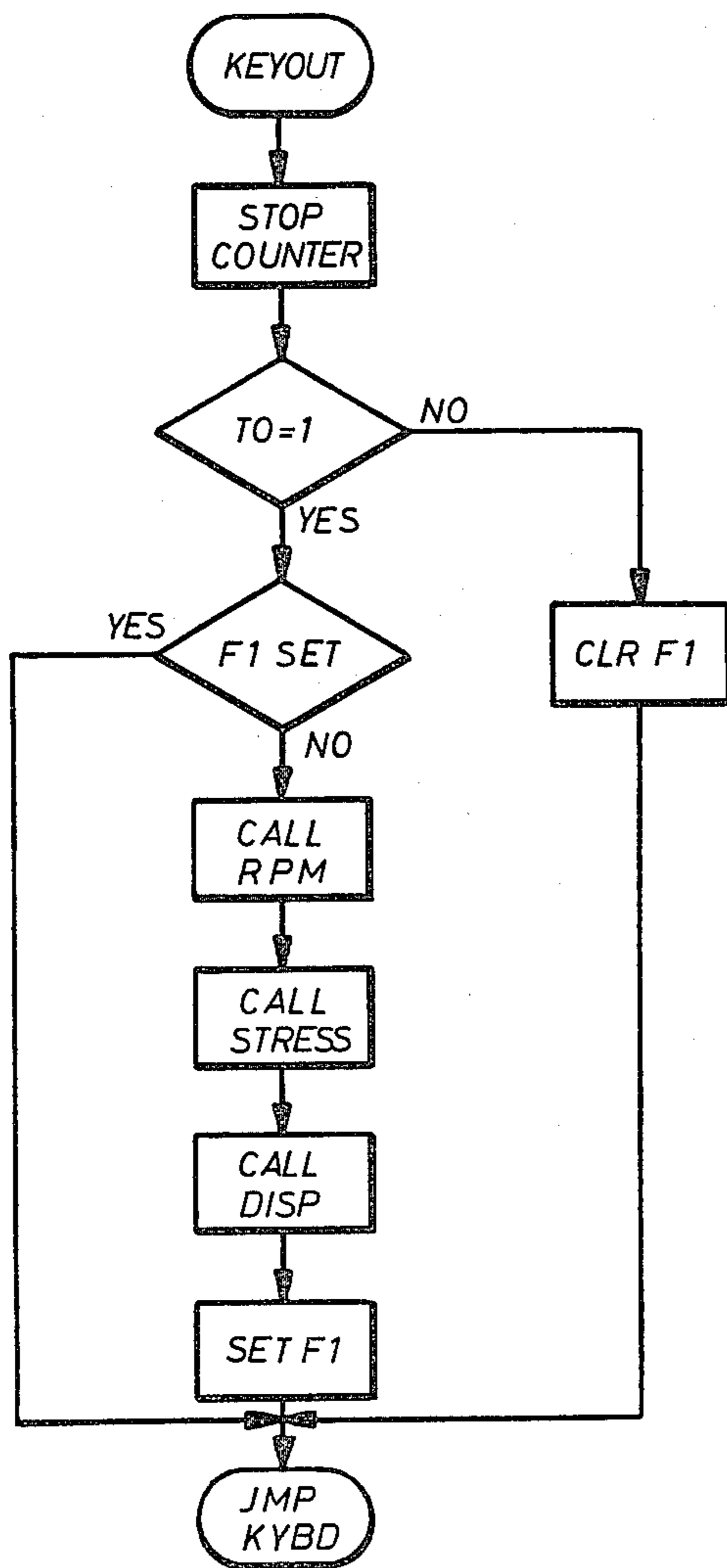


FIG. 11

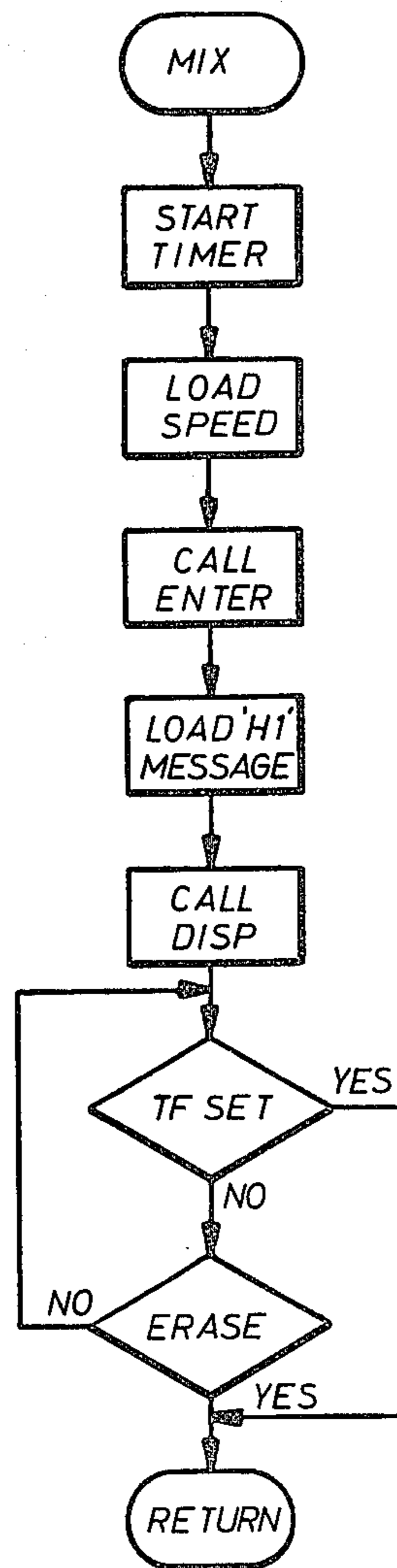


FIG. 12

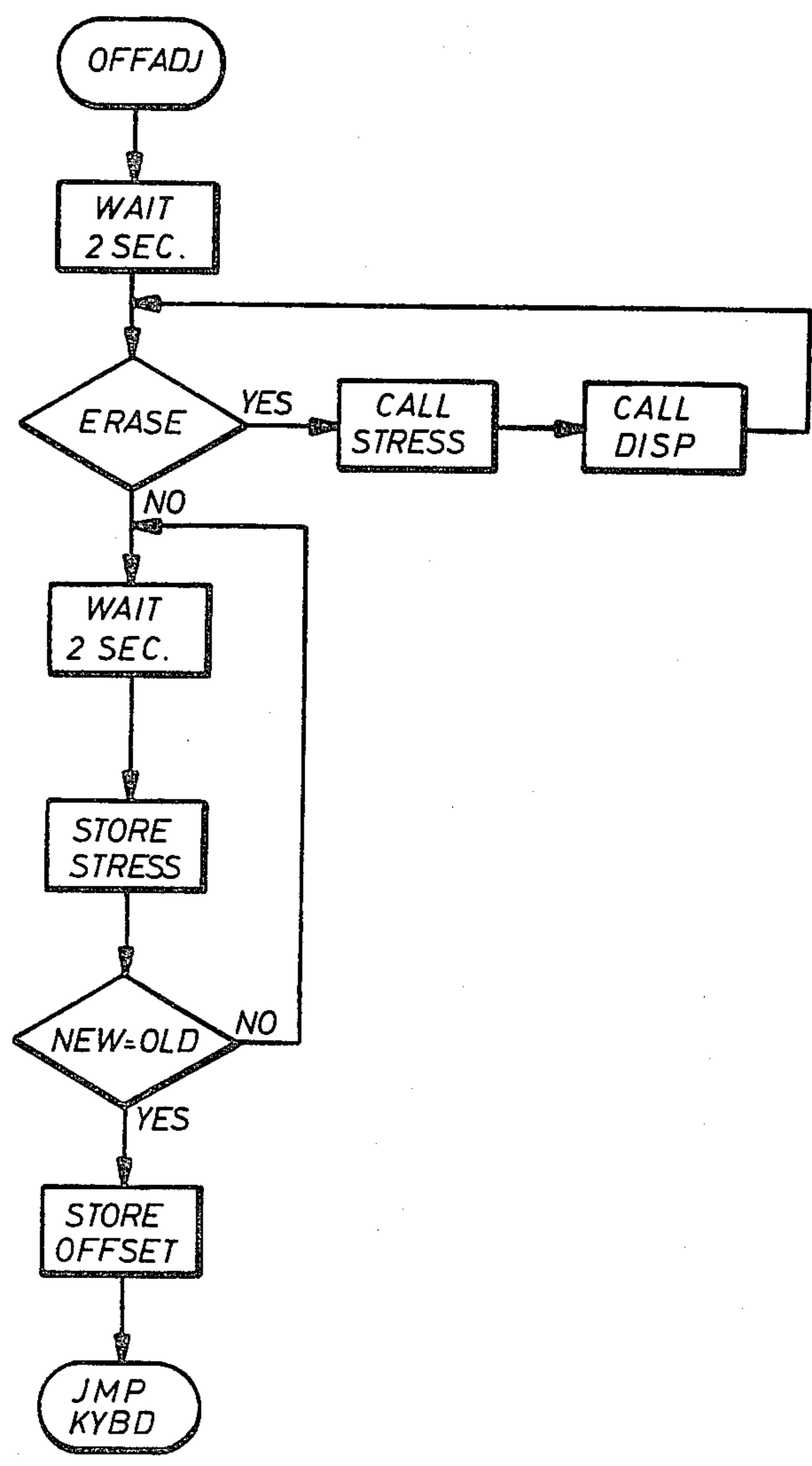


FIG.13

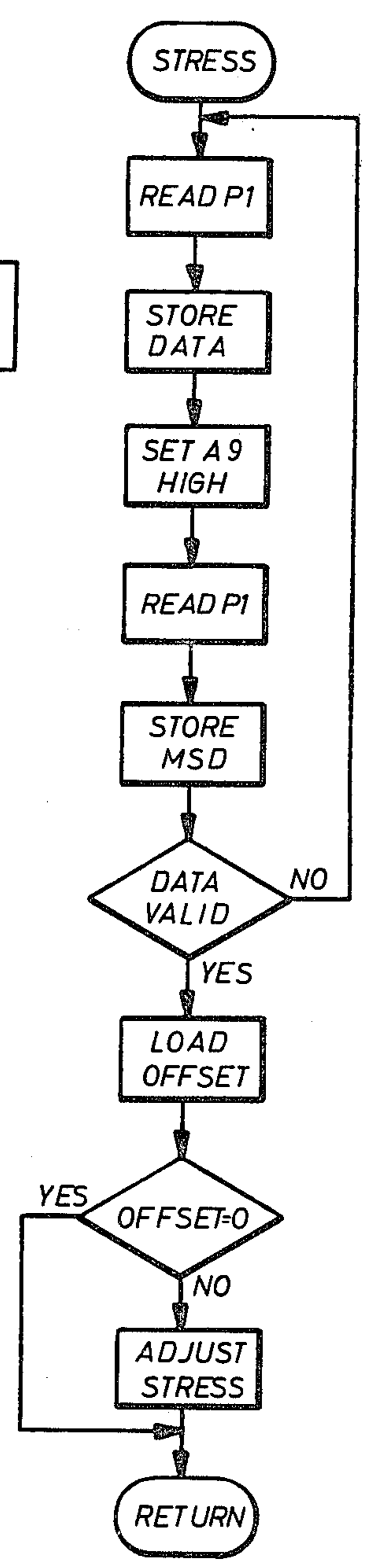


FIG.14

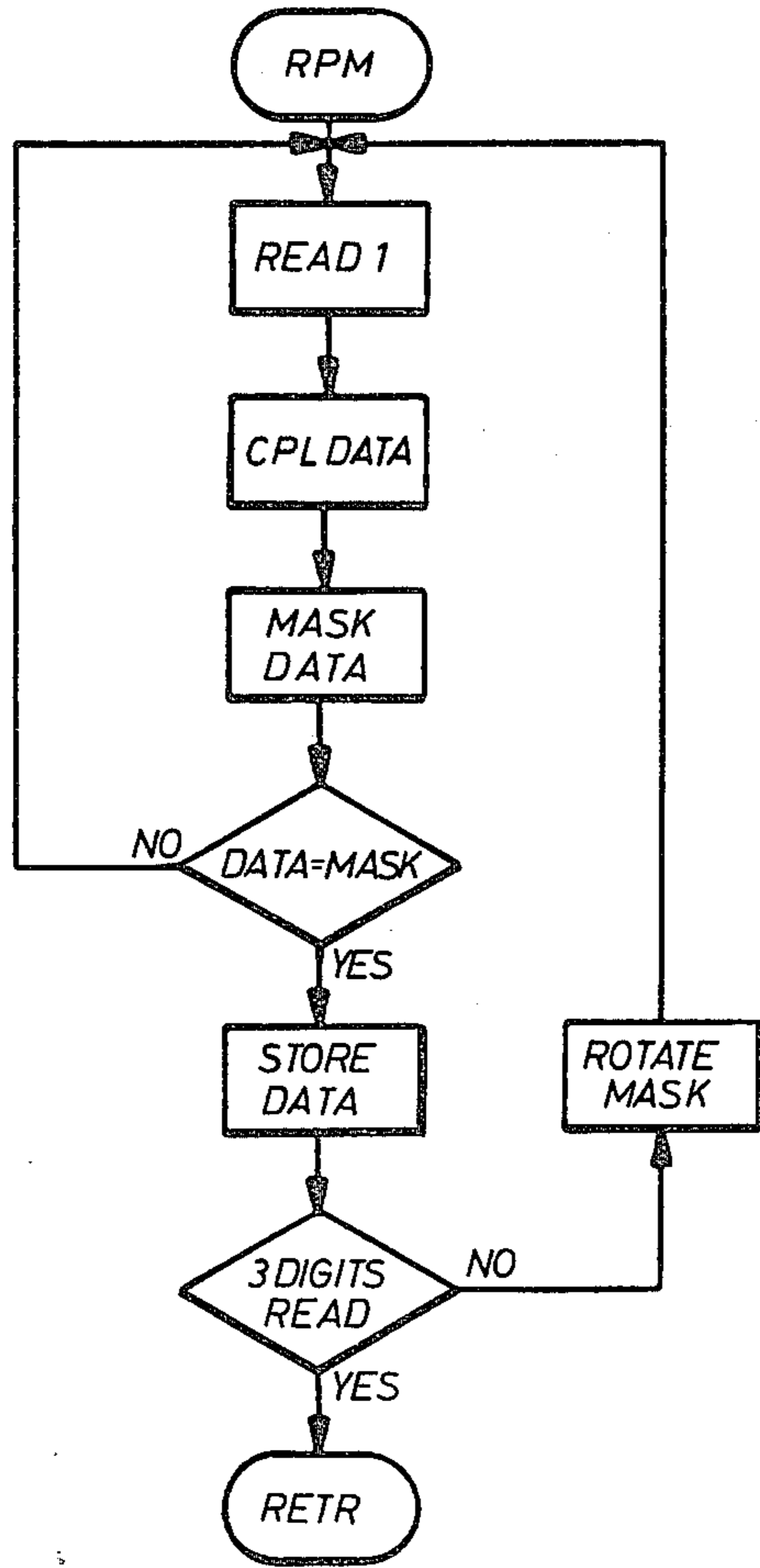


FIG. 15

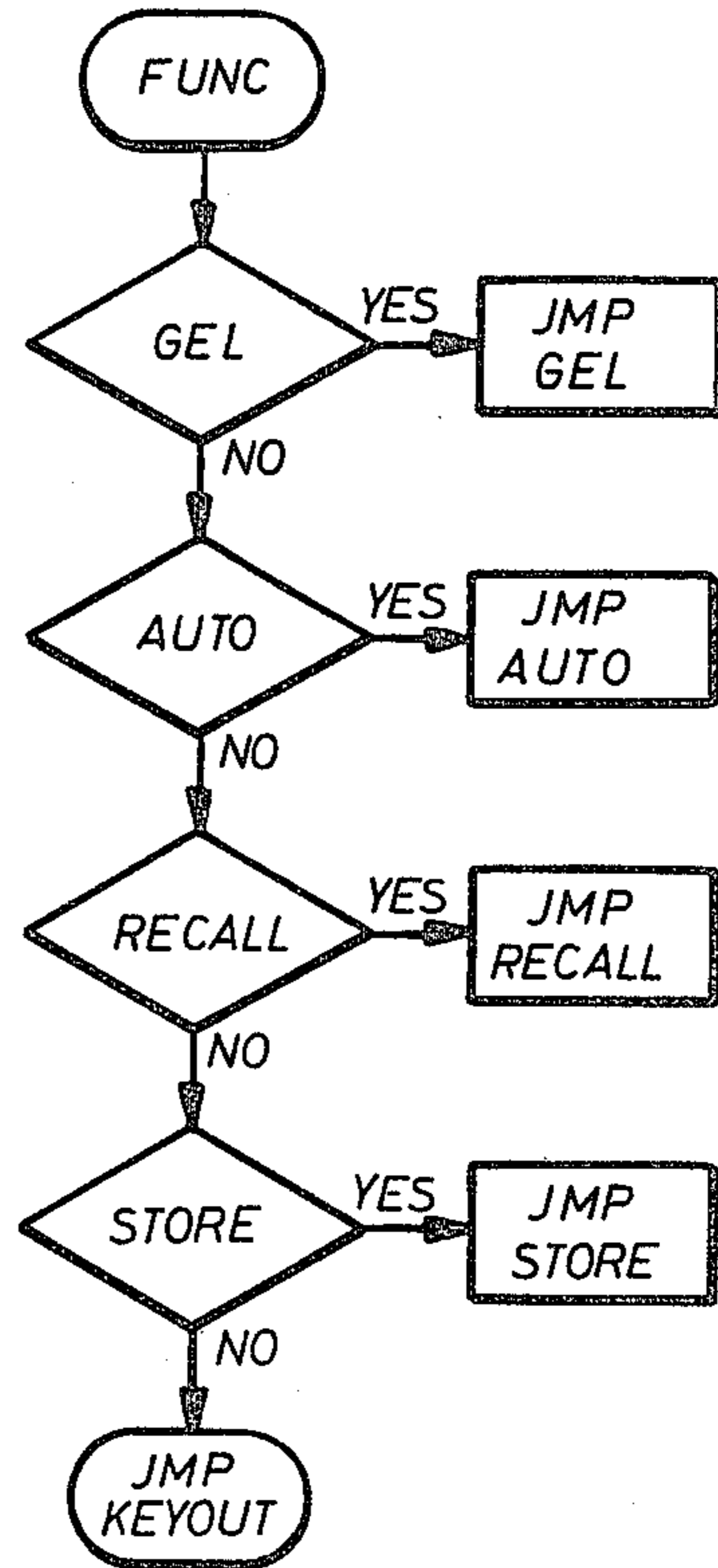


FIG. 16

ROTATIONAL VISCOMETER

BACKGROUND OF THE INVENTION

This invention relates to rotational viscometers for measuring rheometric properties of a fluid. More particularly, this invention relates to a microprocessor controlled rotational type viscometer for automatically and accurately obtaining the steady state shear stress of a fluid at various preselected shear rates.

Properties of fluids, such as the shear stress, shear strength, yield stress, plastic viscosity, etc., are important in many different industries. For example, viscometers are widely used in the drilling industry to measure these properties of drilling fluids that are used to drill oil and gas wells. Information obtained with viscometers is important in controlling the effectiveness of the drilling fluid in, (1) removal of cuttings from the bottom of the hole and carrying them to the surface, (2) holding the cuttings and weight material in suspension when circulation is interrupted, (3) releasing the cuttings and any entrained gases at the surface, (4) transmission of hydraulic horsepower to the drill bit, (5) minimizing annular pressure drops so as to avoid fracturing and the resulting loss of circulation in the uncased hole, (6) maximizing bore hole stability by controlling erosional effects on the well bore while circulating, and (7) reducing to a minimum any adverse effects upon the formation adjacent to the bore hole.

Direct-indicating concentric cylinder rotational viscometers powered by means of an electric motor or hand crank have found wide acceptance in the petroleum industry as an acceptable approach to measuring the viscosity of drilling fluid. In such a viscometer, the drilling mud is contained in the annular space between two cylinders. The outer cylinder or rotor sleeve is driven at a constant rotational velocity or shear rate. Located within the outer cylinder is an inner cylinder. The rotation of the outer cylinder in the mud produces a torque on the inner cylinder. A torsion spring restrains rotational movement of the inner cylinder. A dial scale is attached to the inner cylinder, and with rotation of the inner cylinder, indicates on a fixed pointer the angular displacement of the inner cylinder. The torque produced on the inner cylinder by rotation of the outer cylinder rotates the inner cylinder until the torque on the torsional spring is counter balancing the torque exerted by the fluid. At this point, a reading of the viscosity of the fluid may be taken.

However, direct-indicating rotational viscometers suffer from several problems. Primarily, a high degree of accuracy in shear stress readings is difficult to attain when reading from a scale. Fluctuations in the meter scale about an average position occur as a result of changing physical properties of the fluid and the presence of solid particles in the fluid as the outer cylinder is rotated. As a result, the operator reading the scale must interpolate the average position of the scale. The API recommendation Standard Procedure for Testing Drilling Fluids (APIRP 13B, 7th Edition, April 1978) suggest a that before reading the shear stress at a given shear rate, the dial reading should be allowed to come to a "steady value." Heretofore, rotational viscometers had to depend upon the operator's subjective determination of when a "steady value" has been attained. However, a slow drift in the steady dial reading may occur even with relatively stable readings on the dial, i.e. there are relatively small fluctuations in the dial's

position. This drift can be brought about by gradual change in the structure of the fluid. As a result, a quantitative determination of when a steady value or steady state condition of the fluid had been reached is difficult to attain in these prior-art-viscometers.

A further problem in direct-indicating rotational viscometers is the inability of the outer cylinder to change speeds quickly, and at the same time, be capable of maintaining accurate selected shear rate speeds. One such prior-art means for maintaining an accurate shear rate speed in a rotational viscometer is disclosed in U.S. Pat. No. 4,062,225. A phase locked loop (PLL) motor speed control circuit is shown for controlling the shear rate speed of the rotated outer cylinder. Attached to the motor shaft is a high inertia flywheel which functions to dampen out speed variations of the motor at the selected shear rates. Unfortunately, the inertia of the flywheel does not permit a rapid change in the motor speed as the shear rate is changed.

This inability to rapidly change speed becomes especially significant when the viscometer is measuring the "Gel" strength of the fluid. As recommended at Page 6 of the API bulletin identified above, when measuring "Gel" strength, the fluid is mixed at high speed for 10 seconds, stopped for 10 seconds and then run at 3 RPM. The maximum reading is recorded and process of mixing, stopping and running at a low RPM is repeated. For this procedure, it is implied that following the mixing step, the outer cylinder is immediately stopped to allow the fluid to reform. This would not be possible with a motor speed control system utilizing a flywheel to attain high accuracy shear rate control. The inertia of the flywheel requires a significant amount of time for the rotating outer cylinder to come to a stop.

Accordingly, it would be advantageous to provide a rotating type viscometer in which the shear rate speeds can be controlled to a high degree of accuracy, but at the same time, permit rapid changes in the rotation of the outer cylinder. It would also be advantageous to provide a viscometer that could determine quantitatively the steady state condition of the shear stress at each selected shear rate to achieve a high degree of accuracy in shear rate measurements. It would also be advantageous to provide a viscometer that could automatically and accurately measure the shear stress of a fluid at each of a pre-selected number of shear rates to obtain data values which will permit the piece-wise linear approximation to the shear stress profile of the fluid, particularly in the region of actual shear rate conditions encountered in the annulus of a well bore.

SUMMARY OF THE INVENTION

In accordance with this invention, a rotational concentric cylinder viscometer for measuring the steady state shear stress of a fluid at a given shear rate is provided. The fluid, whose viscosity is to be measured, is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder such that rotation of the outer cylinder produces a torque acting through the fluid on the inner cylinder thereby causing the inner cylinder to rotate. The total amount of rotation of the inner cylinder is related to the shear stress of the fluid as measured at the shear rate.

A microprocessor unit is provided to input and output data signals that will select the various shear rates of rotation of the outer cylinder, and measure the resulting amount of rotation of the inner cylinder at each selected

shear rate. A system clock provides several system clock signals to control the various functions and timing of the viscometer. A shear rate controller responds to the system clock and the shear rate selecting data from the microprocessor to rotate the outer cylinder at the selected constant angular velocity. An angular position indicator comprising an absolute value shaft encoder outputs a digital Gray code that is used to indicate the angular position of the inner cylinder.

A function selector means comprising a manually actuated keyboard is connected to the microprocessor input data lines for inputting both the mode of operation of the microprocessor and for inputting the various pre-selected shear rates at which the outer cylinder is to be rotated. A display means is provided to display both a measured shear stress and the angular velocity of the outer cylinder at which the display shear stress was measured.

The shear rate controller that controls the rate of rotation of the outer cylinder includes a programmable frequency divider that responds to the shear rate selecting data from the microprocessor to produce a phase detector clock signal. The phase detector clock signal is produced by dividing the feedback frequency signal obtained from a speed encoder connected to the outer cylinder. The speed encoder is an optical incremental encoder mechanically connected to the outer cylinder for rotation therewith. A motor drive means responds to the phase detector clock signal to generate the excitation signal to the motor that rotates the outer cylinder. This motor drive means includes a phase detector that responds to the system clock and the phase detector clock signal to generate a phase error signal that indicates the phase difference between the phase detector clock signal and a reference signal. Also included is an amplifier that filters and amplifies the phase error signal to produce the motor excitation signal. The motor used to rotate the outer cylinder is a DC-motor of the ironless armature type.

In another aspect of the invention, a method for obtaining the steady state shear stress of a fluid at a selected shear rate using the microprocessor controlled rotating-cylinder viscometer is also disclosed. The method comprises the steps of changing the outer cylinder rotational speed to a selected shear rate, determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken at a predetermined sample rate. The difference between a current average value and the last obtained average value is then obtained. The result is then compared with a predetermined number of degrees to determine if the steady state condition of shear stress has been attained. If not, the process of obtaining a current average value is repeated until the difference is less than or equal to the predetermined number of degrees, at which point the current average value is taken as the steady state shear stress.

In another aspect of the invention, a method for obtaining the instant "GEL" and 10 minute "GEL" using the microprocessor controlled rotating cylinder viscometer is also disclosed. The method comprises the programmed steps of mixing, waiting the appropriate delay time, and starting the outer cylinder at 3 RPM during which the highest shear stress reading obtained in an interval of 20 seconds, corresponding to one complete revolution of the outer cylinder, is stored for later recall.

In yet a further aspect of the invention, a method for obtaining the shear stress profile (shear stress vs. shear rate) of a fluid using the microprocessor controlled rotating-cylinder viscometer is disclosed. The method for determining the steady state shear stress at a selected shear rate is repeated for each of the pre-selected shear rates until all readings have been obtained.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of this invention are set forth in the appended claims. The invention and advantages thereof may best be understood by reference to the following detailed description of the illustrative embodiments read in conjunction with the accompanying drawings which form a part of this specification, and in which corresponding numerals indicate corresponding parts.

In the Drawings:

FIG. 1 is a block diagram representation of the microprocessor controlled rotating-cylinder viscometer of the present invention;

FIG. 2 is a circuit diagram of the phase locked loop controller of the present invention that controls the rate of rotation of the outer cylinder;

FIG. 3 is a circuit diagram of various blocks illustrated in FIG. 1 including the inner cylinder position indicating means, the I/O function decoder and the keyboard entry to the microprocessor;

FIG. 4 is a tabular listing of the program memory allocation for microprocessor 10 of the present invention; and

FIGS. 5-16 are software flow diagrams for the various routines for the programmed microprocessor 10.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS OF THE PRESENT INVENTION

Referring to the figures and first to FIG. 1, a block diagram of the rotational concentric cylinder viscometer of the present invention is shown. A microprocessor 10 functions to control the operations of the rotating viscometer, and to measure the resulting angular rotation of the inner cylinder indicative of the shear stress of the fluid at a given shear rate. The various elements of the viscometer are connected to the microprocessor 10 by way of three data buses, I/O ports P1 (P10-P17) and P2 (P20-P27), and data bus BUS. In the preferred embodiment of the present invention, microprocessor 10 is manufactured and sold by Intel Corporation as its MCS 8749 Microcomputer.

A crystal controlled system clock 20 is provided to generate various frequencies used to control the functions and timing of the viscometer. In the preferred embodiment, system clock 20 outputs seven frequencies illustrated in the following Table 1:

TABLE 1

| F | Frequency (Hz) |
|---|----------------|
| 1 | 4,194,304 |
| 2 | 2,097,152 |
| 3 | 16,384 |
| 4 | 512 |
| 5 | 4 |
| 6 | 2 |
| 7 | 1 |

Frequency f1 is supplied to the microprocessor 20 for its internal timing, f2 is supplied to the programmable keyboard/display interface 72 (FIG. 3), f3 is supplied to the

keyboard encode chip 82 (FIG. 3), f4 is supplied to the motor speed control 28, f5 is supplied to the microprocessor 10 for digit display purposes, f6 is supplied to the motor speed indicator 24 and f7 is supplied to the elapsed timer contained in microprocessor 10.

Command control data is outputted by the microprocessor 10 to initiate various sequences in the elements of the viscometer or to cause data to be applied to the data buses. Operation of the microprocessor controlled viscometer is initiated from a keyboard assembly 12 having 18 buttons. Two of the 18 buttons are used to switch the power on and off to the circuits. The remaining 16 keys are labeled as follows: 10 of the keys contain the digits 0-9, one each of the remaining 6 keys are respectively labeled STORE, RECALL, ERASE, ENTER, AUTO, and GEL. The 10 keys marked with digits 0-9 are used to input numeric data to select the speed for the various shear rates, and to select the memory locations in conjunction with the "STORE" key. The "RECALL" key is used in conjunction with a series of numeric actuated keys to display a stored value. Any speed selected and inputted to the microprocessor 10 from the keyboard and not ENTERED can be erased with the "ERASE" without interfering with the previous selected speed. Automatic programs can be terminated by actuating the "ERASE" key. The functions performed by the "ERASE" key are as follows: It clears entries during a keyboard input sequence; it clears any "Err" messages; it causes an exit from the "GEL" routine while counting elapsed time; it causes an exit from the "GEL" routine during the 20-sec comparison interval; it causes an exit from the "AUTO" sequence during settling time after speed change; it causes an exit from "RECALL"; it causes an exit from "STORE" with no effect on memory contents; it causes an exit during the 10 second mixing interval; and it causes a jump to the calibration routine if depressed during power-up.

All selected speeds have to be entered with the "ENTER" key. The functions of the "ENTER" key are as follows: It loads the keyboard input data into the programmable divider 26; it starts the comparison routine in "GEL" at the displayed elapsed time; and it causes a return to the main program after completion of the calibration routine. All keyboard actuated numbers are displayed, with the keyboard indicator light on, until it is entered into memory. At that time, the display 16 will indicate the actual speed of the rotating outer cylinder and the resulting steady state shear stress. Any invalid number inputted will display an error "Err". The function of the "AUTO" and the "GEL" keys, will be described in detail below.

The viscometer of the present invention may be operated either in an automatic or a manual mode. In the automatic mode, "AUTO", the steady state shear stress for each of a predetermined number of preselected shear rates will be obtained and stored in memory. This data can then be used to obtain a piece-wise linear approximation to the viscosity profile of the fluid at various shear rates. In order to perform the automatic determination of the shear stress, the keyboard 12 key labeled "AUTO" must be depressed.

When the viscometer is operated in a manual mode, it is possible to preselect the speed at which the outer cylinder is to be rotated by inserting the desired rotation rate via the numbered keys and depressing the "ENTER" key. The outer cylinder will begin to rotate at the inputted speed. When the operator is satisfied that the

steady state value of the shear stress has been attained, depressing the "STORE" button and a numeric button corresponding to a memory location will cause the microprocessor 10 to read both the actual speed of the outer cylinder, via motor speed indicator 24, and the resulting shear stress. This data will be stored in the memory location corresponding to the numeric key depressed after the "STORE" key. During the manual mode of operation, the measured speed and shear stress data are outputted to two 3-digit displays 16.

Still referring to FIG. 1, control of the rotation of the outer cylinder 36 is achieved through the combination of microprocessor 10, programmable divide-by-N counter 26, motor speed control 28 and the DC-motor 30. In particular, the pre-selected or manually entered shear rate data is outputted by microprocessor 10 as a divide factor N to programmable divide counter 26. Counter 26 divides a feedback frequency signal 5 outputted by an optical incremental encoder 32 that is coupled to the rotation of motor 30. The rate of rotation of motor 30 controls the frequency of the feedback frequency signal 5 that is inputted both to the programmable divide counter 26 and to the motor speed indicator 24. The function of motor speed indicator 24 is to produce a digital code word that indicates the actual rotational speed of the motor that is occurring. The output of motor speed indicator 24 is applied as data input to the microprocessor 10, and is read under control of the micro processor.

The output of programmable divide-by-N counter 26 is applied to motor speed control 28 where it is compared with a reference frequency supplied by system clock 20. For the presently preferred embodiment the reference clock signal is f4, 512 Hz. The phase difference between the reference frequency and the output of the programmable counter 26 is a phase error signal that is filtered and amplified to produce the excitation signal to DC-motor 30. Rotation of the output shaft of motor 30 is reflected as a feedback frequency signal 5. When the feedback frequency signal 5 reaches the proper frequency, as determined by the divide factor N and the reference frequency from system clock 20, the excitation signal to DC-motor 30 will remain constant to cause motor 30 to run at the desired velocity. Variations of the motor 30 speed will be reflected as a variation in the feedback frequency signal 5. These variations will produce an appropriate change in the motor excitation signal to bring the motor speed back to the desired setting.

In the presently preferred embodiment of the invention, the DC-motor 30 is a permanent magnet DC-motor having an armature wound on a hollow non-magnetic core. Motors such as these having no magnetic material in the armature or rotor are known as "Ironless motors." A suitable motor of the ironless type is manufactured and sold by Interelectric Corporation of Switzerland as a Maxom DC-motor series 2332 and by Dr. Faulhaber Company of Germany as series 3557. An ironless motor is desirable because of its low inertia and fast acceleration. These features enable the motor to achieve a fast reacting precision motor control, and a short settling time.

Referring now to FIGS. 1 and 2, the concentric rotating cylinders 36 respond to rotation of the DC-motor 30 to produce a corresponding rotation in the shaft of the inner cylinder. This angular rotation is monitored by absolute value shaft encoder 38 that outputs a digital code word indicative of the actual angular position of

the inner cylinder. This digital data is inputted to a code converter 34 whose output is coupled onto one of the microprocessor 10 data buses, P10-P17. In the presently preferred embodiment, absolute value shaft encoder 38 outputs a 9-bit Gray code where only one bit line is permitted to change per interval of angular rotation of the encoder shaft. The position encoder 38 is graduated from -9° to $+350^\circ$ deflection. The code converter 34 converts the Gray code of encoder 38 into its BCD equivalent values. Code converter 34 consists of a ROM having the BCD equivalent codes stored in memory locations that are addressed by the output code words from the encoder 38. Each output code word from encoder 30 serves as a unique address to the code converting ROM.

To perform the code conversion, a 9-bit address to the code converting ROM contained in converter 34 is generated by the encoder 38. The most significant bit of the 10-bit address to the ROM is inputted from the microprocessor 10 on the P23 data bus line. Under program control, microprocessor 10 causes I/O decoder 80 to generate the strobe D to multiplex onto data bus lines P10-P17 two BCD digits of the three BCD digits that represent the angle of the inner cylinder's shaft. Data bus P23 is then set and strobe D generated to output from the code converting ROM the third BCD digit along with the + or - sign for the angle. The encoder disk 35 of encoder 38 is properly etched to produce the Gray code. To produce the electrical signals to read the etched disk 35, the present invention uses a Texas Instruments light emitting diode array T1L 49 and a photosensitive transistor array T1L629.

Turning now to FIG. 2, the motor speed indicator 24, programmable divider counters 26 and motor speed control 28 are illustrated in more detail. The encoder 32 consists of a rotatable disc 40 having slits or means therein for permitting the passage of light from light emitting diode D1 to reach the base of light sensitive transistor Q1. The output of transistor Q1 is amplified and applied to comparator A1 to produce a digital signal at the input of exclusive OR gates 44. The output of exclusive OR gates 44 comprises the feedback frequency signal 5. For the preferred embodiment, encoder 32 produces 3840 pulses per revolution on the output shaft of outer cylinder 36. At a rotor speed of 600 RPM, encoder 32 produces a frequency of 76,800 pulses per second.

As previously discussed, the feedback frequency signal 5 is applied to programmable divider 26 to produce the phase frequency signal on its output. This signal is applied as one input to two input NAND gate 60. Inverter 58 responds to a control signal from data bus P25 to provide the other input to NAND gate 60. Control signal P25 functions to select the phase frequency clock from programmable divider 26 as the input signal to phase detector 68 for all rotor speeds above 1 RPM. When a rotor speeds of 1 RPM is desired, the microprocessor 10 outputs a control signal on P25 to select the feedback frequency signal 5 as the frequency to be applied directly to phase detector 68 by way of NAND gates 62 and 64.

As illustrated in FIG. 2, NAND gates 58, 60, 62 and 64 function as an AND/OR gate to select either the output of the programmable divider 26 or the feedback frequency signal 5 as the input clock signal to phase detector 68 depending upon the state of data bus line P25. The divide parameter N from the divide-by-N counter 26 is supplied to the programmable divider 26

from the microprocessor 10 BUS. Programmable divider 26 is manufactured and sold by Intel Corporation as a model 8253 divide-by-N counter. Prescaler counter 52 which forms part of the motor speed indicator 24 is contained in the Intel 8253 chip.

Also inputted to the motor speed control circuit 28 is a second control signal, P27, from microprocessor 10. This signal enables the phase detector 68 to generate an excitation signal to the motor 30 to cause it to begin rotation. When data bus line P27 is not active, motor 30 will not rotate. When enabled by P27, the 512 Hz frequency signal f4 from the system clock 20 is applied to phase detector 68 which, for the preferred embodiment of the present invention, is manufactured and sold by Motorola Incorporated as a phase/frequency detector MC14568. This particular phase detector contains a divide by 4 internal counter to reduce the 512 Hz reference signal down to 128 Hz. The phase detector 68 produces an error signal representative of the phase difference between the signal from the encoder 32 divided by the division ratio N, and the 128 Hz reference signal. This error signal is filtered and amplified by amplifier A2 and power amplifier Q3 to provide the excitation signal to the motor. It should be clear that the values of the various circuit components, voltages, and their manufacturer type numbers depicted in FIG. 2 and described above will vary depending upon the intended use. In a presently preferred embodiment use in connection with a phase locked loop control system to control the speed of rotation of motor 30, Table 2 below sets out exemplary values which have been found satisfactory.

TABLE 2

| REFERENCE | VALUE (ohms) | REFERENCE | TYPE or VALUE |
|-----------|-----------------|-----------|-----------------------------|
| R1 | 120 | C1 | 820pf |
| R2 | 1K,VAR | C2,C6 | .1 f |
| R3 | 47K | C3,C7 | .001 f |
| R4,R6,R12 | 100K | C4 | 1 f |
| R5,R9 | 1K | C5 | 10 f |
| | | D1 | OPTRON INC. 81355 |
| R7, R13 | 100K,VAR | D2 | 55T |
| R8 | 330K | Q1 | OPTRON INC. 81355 |
| R10, R11 | 10K | Q2 | 2N4123 |
| R14 | 6.8K | Q3 | MJE6044, 2N6388 |
| R15 | 39 | A1 | LM311, MLM311 (National) |
| | | A2 | LM358, MLM358 (Motorola) |

Still referring to FIG. 2, the motor speed indicator 24 for determining the actual speed of rotation of the motor 30 is shown. The feedback frequency signal 5 is applied to a divide by 64 pre-scaler 52 to reduce the frequency generated by encoder 32. This reduced frequency is applied to a 3-digit BCD counter 54 that is periodically cleared by the 2 Hz reference signal f6 from the system clock 20. Counter 54 is manufactured and sold by Motorola as model MC14553. The 3-digit counter 54 functions to generate a 3-digit BCD code equal to the number of pulses produced in a time interval of one second, and multiplexes each digit sequentially onto its output. The multiplexed output of the 3-digit counter 54 is applied to a tri-state buffer circuit 56 that responds to function strobe A from decoder 22 to apply the BCD digits onto the microprocessor bus P10-P16. Also strobed onto the data bus lines P10-P16 are the digit selection bits that indicate which of the three BCD digits from counter 54 is currently being

multiplexed into the buffer 56. For the presently preferred embodiment, buffer 56 is a Texas Instruments tri-state buffer model SN74LS244. The control signal A is generated in response to function control data outputted by microprocessor 10 when a reading of the speed of rotation of the outer cylinder 36 is desired.

Turning now to FIG. 3 in which various functions illustrated in FIG. 1 are illustrated in more particular detail, the absolute value shaft encoder 38 is shown responding to the rotatable inner cylinder 37 of the concentric rotating cylinders. The encoder 38 functions in a similar manner to the optical encoder 32 in that light emitting diodes D3-D11 are used to produce light that is applied to the bases of transistors Q4-Q12 through a disc that rotates with the shaft of the inner cylinder 37. Each output of transistors Q4-Q12 is applied to a respective buffer gate 70 to produce the 9-bit digital code representative of the angular position of the inner cylinder 37. As previously mentioned, the 9-bit Gray code word is applied to code converter 34 for conversion to BCD digits that are applied to the microprocessor data bus lines P10-P17. The data from the encoder 38 is applied to the bus through the code converter 34 in response to function strobe D outputted by the I/O function decoder 22.

The I/O function decoder chip 22 which generates the various function strobe signals is of a 1-of-8 decoder that responds to the microprocessor 10 data bus lines P20-P22 to produce eight strobes used to control various sequencies and to enable data to be inputted to the microprocessor 10 data buses. For the preferred embodiment, decoder 22 is manufactured and sold by Intel Corporation as model 8205. Also illustrated in FIG. 3 is the system clock 20. It will be appreciated by those of ordinary skill in the art that the basic reference frequency produced by a crystal controlled oscillator may be divided down by counters to produce the reference frequencies illustrated. Accordingly, the circuits for this function are not shown and discussed herein.

Further illustrated in FIG. 3 is the keyboard 12 consisting of 16 keys that are used to input the data to the microprocessor 10 needed to operate the viscometer. The output from the various keys are applied to the keyboard encoder 82. Encoder 82 responds to the the 16 KHz reference frequency f3 from the system clock 20 to produce the 4-bit binary code eventually applied through the buffer gates 84 to the microprocessor 10 input data bus lines P10-P13. Function strobe B enables gate 84 to apply the 4-bit code words onto the data lines. Also produced in the keyboard encoder 82 is a strobe signal that is applied to the display interface 72 which generates an interrupt request signal to microprocessor 10. The strobe signal is only produced when one of the numeric keys is depressed. The actuation of one of the mode control keys to the microprocessor 10 does not produce an immediate response from the microprocessor. Rather, the internal software routines will periodically read the output from the keyboard buffer gates 84 and determine if any of the function keys have been depressed.

Still referring to FIG. 3, the two 3-digit displays 16 are shown diagrammatically as composed of 7-segment display digits 74 that respond to digital driver 76 and display interface 72. The digits to be displayed in the digits 74 are loaded from the microprocessor 10 BUS lines into the display interface 72 on the occurrence of the control signal E from the I/O function decoder 22. The various digits to be displayed are serially loaded

into display interface 72 which time multiplexes the digits onto the control lines to the digits of display 74. In this manner, the data stored in display interface 72 appears to be continuously displayed by the display unit 74. The presently preferred embodiment has used an Intel Corporation 8279 display chip for display 16.

As previously mentioned, the present invention is able to determine the steady state value for the shear stress at each of the preselected rotor speeds. Shortly after application of power to the electronic circuits, the microprocessor 10 measures the angular position of the inner cylinder at zero speed to determine if an offset error is present. This offset error is used to correct all further angular position measurements. Upon entry into the automatic mode by microprocessor 10, the outer cylinder is rotated at 700 RPM for a period of 10 seconds to mix the fluid. Mixing is required to cause a breakdown of all particle bonds for particles suspended in the fluid. At the end of the 10 second interval, the outer cylinder is then rotated at 600 RPM a period of 2 seconds to allow for the speed of the outer cylinder 36 to stabilize and become phase locked to the fixed reference signal from the system clock 20. Readings of the angular deflection as reflected from absolute value shaft encoder 38 are then taken at a sample rate of 128 samples/second for one second.

Characteristic of all concentric rotating cylinder viscometers is the presence of fluctuations in the angular position of the inner cylinder 37 due to random variations in the torque transmitted by the fluid to the inner cylinder 37. The magnitude and rate of the fluctuations may vary from fluid sample to fluid sample depending on the amount and size of the solid particles present. For the present invention, it is important that the sample rate of angular position readings of the inner cylinder 37 be at least two times the maximum rate of fluctuations present in the angular position of the inner cylinder. As the readings are taken, they are consecutively totalized until all of the readings have been taken. Then, the total is divided by the number of samples taken, 128, to give an average angular deflection of the inner cylinder position for that one second measuring interval. The presence of solid particles in the fluid being tested can exert intermittent or irregular forces on the cylinder thus causing the cylinder to oscillate about a mean angular position. The averaging sequence eliminates the need for a mental averaging by the operator to obtain this mean, and thereby reduces the possibility of an error in the reading.

Many fluids exhibit thixotropic properties and require a certain time period for particle bonds to reform after a reduction in shear rate. After all bonds that can exist at a particular shear rate have reformed, the shear stress will reach an equilibrium value and a reading may be taken. For this reason, the averaging sequence is performed again after a two second time interval. The next average value thus obtained is compared to the previous average value, and if the two values are within plus or minus one degree ($\pm 1^\circ$) of each other, the current average value is accepted as the true equilibrium or steady state reading. If the current average value differs in magnitude by more than one degree from the previous average value, another two second time interval elapses and the averaging process is again repeated. This procedure continues until the difference between the present and previous readings are within the desired range.

After the steady state reading has been determined, that reading, along with the shear rate at which it was

obtained, is stored in a memory location for later recall and display. In one embodiment of the present invention, the rotational speeds of 600, 300, 200, 100, 60, 30, 15, 6 and 3 RPMs are recommended to obtain shear stress readings that will permit the piece-wise linear approximation of the shear stress versus shear rate curve, and allow the operator to make calculations on certain rheometric properties of the fluid. The various shear rates to obtain the shear stress profile would have been inputted into the microprocessor 10 prior to initiating the automatic mode of operation. The above described procedure for obtaining the steady state shear stress at a shear rate would then be repeated for each of the preselected and inputted shear rates until the measurements of shear stress at each of the speeds has been obtained.

In the automatic mode, after all of the preprogrammed shear rate readings have been measured and recorded, the microprocessor 10 proceeds to the GEL mode. This GEL mode is also separately selectable by the operator by depressing the button on the keyboard marked "GEL." Upon initial entry into the GEL mode, the outer cylinder 36 is rotated at 700 RPM for a period of 10 seconds. Again to mix the fluid under test and to break down particle bonds that give the fluid thixotropic properties. After the mixing period, the outer cylinder rotation is stopped and the elapsed time counter interval to microprocessor 10 is initiated to generate the elapsed time. The microprocessor 10 internal elapse time counter is incremented once every second by f7, and upon reaching 10 seconds, the outer cylinder 36 is

rotated at 3 RPM. Immediately as the outer cylinder 36 starts to rotate at 3 RPM, readings of the angular displacement of the inner cylinder 37 are taken in rapid succession for a period of 20 seconds corresponding to one complete revolution of the outer cylinder 36. During this 20 second time period, the largest value is retained, and after the 20 second period, this maximum value is stored in an operator specified addressable memory location for later recall. This stored reading corresponds to the initial GEL strength of the fluid under test. The fluid is then mixed as before and then the same sequence of measurements occur after a second time period of 10 minutes. The elapse timer can be interrupted manually by depressing the ENTER button and with this manual override, any time GEL, up to 600 seconds can be taken. When all measurements are completed, the microprocessor 10 exits the GEL routine and leaves the outer cylinder rotating at 3 RPM with the display showing the speed and corresponding shear stress reading.

Referring now to FIGS. 5-16, software flow diagrams for various functions performed by the present invention are shown. These flow diagrams illustrate the functions performed by microprocessor 10 in response to the various modes of operation keyed from keyboard 12. The following is an assembler language listing of the microprocessor 10 program that implements the flow diagrams of FIGS. 5-16. It will be appreciated by those skilled in the art that other routines other than those illustrated and described herein could be programmed into microprocessor 10 and achieve the same results.

```

1  TITLE( 8749 2K RHEOMETER PROGRAM V2
2  MACROFILE  DEBUG XREF PAGEWIDTH (80) NOGEN
3  WRITE     MACRO PORT2,DBUS
4           MOV A, #PORT2
5           OUTL P2,A
6           MOV A, #DBUS
7           OUTL BUS,A
8           ENDM
9  PREP     MACRO AND,OR,PORT
10          ANL P2,#AND
11          ORL P2,#OR
12          MOV A,#PORT
13          OUTL BUS,A
14          ENDM
15  TAB7    EQU 0ECH
16          MOV A,#0GH           ;RESET 8279
17          OUTL P2,A
18          NOP
19          ANL P2,#00H
20          MOV RO,#18H         ;CLEAR RAM 18 to 7F
21          MOV R7,#68H
22          CLR A
23  CLEAR:  MOV @RO,A
24          INC R0
25          DJNZ R7,CLEAR
26          WRITE 15H, 06H     ;SET KYDB/DISP MODE
31          MOV A,#35H
32          OUTL BUS,A         ;PROGRAM 8279 CLOCK
33          MOV A,#0C3H
34          OUTL BUS,A         ;CLEAR ALL IN 8279
35          MOVA,#80H
36          MOV T,A
37          STRT T
38          JTF +4
39          JMP -2
40          STOP TCNT
41          WRITE 1BH, 16H     ;PROGRAM 8253 CNT 0
46          MOV A,#56H
47          OUTL BUS,A         ;PROGRAM 8253 CNT 1
48          MOV A,#0B5H
49          OUTL BUS,A         ;PROGRAM 8253 CNT 2
50          WRITE 0BH,40H     ;LOAD CNT 1
55          WRITE 13H,00H
60          MOV A,#01H

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61      OUTL BUS,A
62      MOV A,#02H
63      OUTL P2,A          ;SET FOR KYBD INPUT
64      JMP OFFADJ
65  KYBD: ANL P2,#0A0H
66      ORL P2,#02H
67      JNI FUNC
68      MOV R7,#04H
69  STAT: JNI DATIN
70      MOV R0,#18H
71      ANL P2,#0E0H
72      ORL P2,#42H
73      IN A,P1          ;INPUT KYBD DATA
74      ANL A,#0FH
75      XCH A,@RO
76      INC R0
77      XCH A,@RO
78      INC R0
79      MOV @RO,A
80      MOV R0,#18H
81      MOV R1,#1BH
82      MOV R6,#03H
83      MOV A,@RO
84      MOV @R1,A
85      INC R0
86      INC R1
87      DJNZ R6,$-4
88      CALL DISP
89      CALL CLRIFIF
90      DJNZ R7,STAT
91      JMP ERROR
92  DATIN: ANL P2,#0E0H
93      ORL P2,#02H
94      IN A,P1
95      ANL A,#0FH
96      MOV R5,A
97      XRL A,#0AH
98      JZ ERASE          ;TEST FOR 'ERASE'
99      MOV A,R5
100     XRL A,#0BH
101     JZ ENTIN          ;TEST FOR 'ENTER'
102     JMP STAT
103  ERASE: CLR A
104     MOV R0,#18H
105     MOV R7,#06H
106     MOV @RO,A
107     INC R0
108     DJNZ R7,$-2
109     JMP KEYOUT
110  ERROR: MOV R0,#1BH          ;LOAD 'ERR' MESSAGE
111     IMP (13H, 13H)
112     MOV @RO, #M
113     INC R0
114     ENDM
119     MOV @RO,#0FH
120     CALL DISP
121     ANL P2,#0E0H
122     ORL P2,#02H
123     IN A,P1
124     ANL A,#0FH
125     XRL A,#0AH
126     JZ ERASE          ;TEST FOR 'ERASE'
127     JMP $-7
128  ENTIN: MOV R0,#1AH          ;TOTAL KYBD REGISTER
129     MOV A,@RO
130     DEC R0
131     ADD A,@R0
132     MOV R7,A
133     DEC R0
134     ADD A,@R0
135     JZ MOTOFF
136     DEC A
137     JNZ GOENT
138     MOV A,R7
139     JNZ GOENT
140     MOV a,#0A0H
141     OUTL P2,A
142     MOV R0,#18H
143     CLR A
144     MOV @R0,A
145     INC R0
146     MOV @R0,A

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147      INC R0
148      MOV @R0,A
149      JMP KEYOUT
150  MOTOFF:  CLR A          ;TURN MOTOR OFF
151      OUTL P2,A
152      JMP KEYOUT
153  GOENT:   CALL ENTER
154      JMP KEYOUT
155  FUNC:    IN A,P1       ;CHECK KYBD FUNCTIONS
156      ANL A,#0FH
157      MOV R5,A
158      XRL A,#0CH
159      JNZ $+4
160      JMP GEL
161      MOV A,R5
162      XRL A,#0DH
163      JNZ $+4
164      JMP AUTO
165      MOV A,R5
166      XRL,#0EH
167      JNZ $+4
168      JMP RECALL
169      MOV A,R5
170      XRL A,#0FH
171      JNZ $+4
172      JMP STORE
173      JMP KEYOUT
174  GEL:     CALL GMESS
175          CALL MIX
176          MOV R4,#0F6H   ;R4=CNT START CODE
177          MOV R5,#26H   ;R5=STORAGE ADDRESS M
178          MOV R6,#01H   ;R6=NO. OF TF OVERFLO
179          MOV R7,#00H   ;R7=100's of SEC CNTR
180  STOPMO:  CLR A
181          OUTL P2,A
182          MOV A,#0FEH
183          MOV T,A
184          STRT CNT
185          MOV A,R5
186          MOV R0,A
187          CLR A
188          MOV @R0,A     ;CLEAR STORAGE MEMORY
189          DEC R0
190          MOV @R0,A
191          DEC R0
192          MOV @R0,A
193          JTF $+4
194          JMP $-2
195          STOP TCNT
196          CALL GMESS
197  COUNT:   MOV A,R4
198          MOV T,A
199          STRT CNT      ;START TIMER
200  TFTEST:  JTF LOOPS
201          MOV A,#02H
202          OUTL P2,A
203          IN A,P1
204          ANL A,#0FH
205          MOV R3,A
206          XRL A,#0BH   ;TEST FOR 'ENTER'
207          JNZ $+4
208          JMP GOGEL
209          MOV A,R3
210          XRL A,#0AH   ;TEST FOR 'ERASE'
211          JZ GELOUT
212          MOV A,T
213          CPL A
214          ADD A,R4
215          CPL A
216          MOV R2,A
217          MOV R1,#00H
218          MOV R0,#1BH
219  TENS:    MOV A,R2
220          CPL A       ;CONVERT TIMER VALUE
221          ADD A,#0AH  ;TO 2 BCD NUMBERS
222          JC ONES
223          INC R1
224          CPL A
225          MOV R2,A
226  ONES:   JPM TENS
227          MOV A,R2
228          MOV @R0,A

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229          INC R0
230          MOV A,R1
231          MOV @R0,A
232          INC TO
233          MOV A,R7
234          MOV @R0,A
235          CALL DISP
236          JMP TFTEST
237  LOOPS:   DEC R6
238          MOV A,R6
239          JZ GOGEL
240          INC R7
241          JMP COUNT
242  GOGEL:   STOP TCNT
243          MOV A,#0ECH
244          MOV T,A
245          STRT CNT
246          MOV A,R5
247          ADD A,#1FH
248          MOV R0,A
249          MOV R1,A
250          MOV @R0,#0EH          ;LOAD 'G-N' MESSAGE
251          DEC R0
252          MOV @R0,#0AH
253          DEC R0
254          MOV A,R1
255          JBO $+6
256          MOV @R0,#02H
257          JMP $+4
258          MOV @R0,#01H
259          MOV R0,#18H
260          MOV R3,#02H
261          MOV @R0,#03H          ;LOAD 003 RPM
262          INC R0
263          CLR A
264          MOV @R0,A
265          INC R0
266          MOV @R0,A
267          MOV R0,#1BH
268          DJNZ R3,$-9
269          CALL ENTER
270          CALL DISP
271  MAGCOM:  CALL STRESS
272          MOV R0,#20H          ;PREVENT NEG READINGS
273          MOV A,@R0
274          XRL A,#0AH
275          JZ MAGOUT
276          MOV A,R5
277          MOV R1,A
278          MOV A,@R1
279          MOV R3,A          ;R3=OLD DATA
280          MOV R0,#20H
281          MOV A,@R0
282          MOV R2,A          ;R2=NEW DATA
283          CALL COMP
284          JF1 MAGOUT          ;F1=[R3 R2]
285          JNZ STOMAX          ;[A=0] = [R3=R2]
286          CLR C
287          DEC R0
288          DEC R1
289          MOV A,@R1
290          DEC R1
291          SWAP A
292          ADD A,@R1
293          MOV R3,A
294          MOV A,@R0
295          DEC R0
296          SWAP A
297          ADD A,@R0
298          MOV R2,A
299          CALL COMP
300          JF1 MAGOUT
301          JNZ STOMAX
302          JMP MAGOUT
303  STOMAX:  CALL STODAT          ;STORE NEW DATA
304  MAGOUT:  JTF AGAIN
305          MOV A,#82H
306          OUTL P2,A
307          IN A,#82H
308          ANL A,#0FH
309          XRL A,#0AH          ;TEST FOR 'ERASE'
310          JNZ MAGCOM

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311      JMP GELOUT
312  AGAIN:  MOV A,R7
313      JNZ GELOUT
314      CALL GMESS
315      CALL MIX
316      MOV R4,#9CH      ;RESET PARAMETERS
317      MOV R5,#23H
318      MOV R6,#06H
319      JMP STOPMO
320  GELOUT: STOP TCNT
321      CLR F1
322      JMP KEYOUT
323  AUTO:   CALL AUMESS
324      CALL MIX
325      MOV R4,#08H
326      MOV R6,#0D4H    ;START OF SPEED DATA
327  LOAD:   MOV A,#0FEH
328      MOV T,A        ;START 2 SEC TIMER
329      STRT CNT
330      MOV R0,#1AH
331      MOV R1,#1DH
332      MOV R7,#03H
333      MOV A,R6
334      MOVP3 A,@A    ;LOAD SPEED DATA
335      MOV @R0,A
336      MOV @R1,A
337      DEC R0
338      DEC R1
339      INC R6
340      DJNZ R7,$-7
341      MOV A,R4
342      INC A
343      RL A
344      ADD A,R4
345      ADD A,#41H
346      MOV R1,A
347      MOV R0,#1BH
348      MOV R7,#03H
349      MOV A,@R0
350      MOV @R1,A
351      INC R0
352      INC R1
353      DJNZ R7,$-4
354      CALL ENTER
355      CALL AUMESS
356      CALL DISP
357      MOV A,#82H
358      OUTL P2,A
359      CLR A
360      MOV R7,#04H    ;CLEAR RAM 7AH TO 7DH
361      MOV R0,#7AH
362      MOV @R0,A
363      INC R0
364      DJNZ R7,$-2
365  RUN:    JTF STEP
366      IN A,P1        ;TEST FOR ERASE
367      ANL A,#0FH
368      XRL A,#0AH
369      JNZ RUN
370      JMP KEYOUT
371  STEP:   STOP TCNT
372      MOV R7,#80H
373      SEL RB1
374      CLR A
375      MOV R4,A
376      MOV R5,A
377      MOV R0,#20H
378      SEL RB0
379  BCDHEX: CALL STRESS
380      MOV R0,#20H    ;PREVENT NEG READINGS
381      MOV A,@R0
382      XRL A,@9AH
383      JNZ $+8
384      CLR A
385      MOV @R0,A
386      DEC R0
387      MOV @R0,A
388      DEC R0
389      MOV @R0,A
390      SEL RB1
391      MOV A,#0BBH
392      MOV T,A

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| | | |
|-----|--------------|-----------------------|
| 393 | STRT T | |
| 394 | JTF \$+4 | |
| 395 | JMP \$-2 | |
| 396 | STOP TCNT | |
| 397 | CLR C | |
| 398 | MOV A,@R0 | |
| 399 | MOV R2,A | |
| 400 | RL A | |
| 401 | RL A | |
| 402 | MOV R3,A | |
| 403 | RL A | |
| 404 | RL A | |
| 405 | RL A | |
| 406 | MOV R2,A | |
| 407 | ADD A,R3 | |
| 408 | MOV R3,A | |
| 409 | MOV A,R2 | |
| 410 | RL A | |
| 411 | ADD A,R3 | |
| 412 | MOV @R0,A | |
| 413 | JNC \$+4 | |
| 414 | INC R5 | |
| 415 | CLR C | |
| 416 | MOV A,R7 | |
| 417 | RL A | |
| 418 | MOV R3,A | |
| 419 | RL A | |
| 420 | RL A | |
| 421 | ADD A,R3 | |
| 422 | MOV R7,A | |
| 423 | ADD A,R6 | |
| 424 | ADD A,@R0 | |
| 425 | JNC \$+4 | |
| 426 | INC R5 | |
| 427 | CLR C | |
| 428 | ADD A,R4 | |
| 429 | JNC \$+4 | |
| 430 | INC R5 | |
| 431 | CLR C | |
| 432 | MOV R4,A | ;R4 CONTAINS HEX SUM |
| 433 | SEL RB0 | ;R5 CONTAINS OVERFLOW |
| 434 | DJNZ R7,\$+4 | |
| 435 | JMP \$+4 | |
| 436 | JMP BCDHEX | |
| 437 | SEL RB1 | ;CALC AVERAGE VALUE |
| 438 | CLR F0 | |
| 439 | CLR C | |
| 440 | MOV A,R5 | |
| 441 | RLC A | |
| 442 | MOV R5,A | |
| 443 | MOV A,R4 | |
| 444 | JB7 \$+4 | |
| 445 | JMP \$+5 | |
| 446 | MOV A,R5 | |
| 447 | INC A | |
| 448 | MOV R5,A | |
| 449 | MOV R0,#7CH | ;DETERMINE IF SYSTEM |
| 450 | MOV R1,#7BH | ;WAS IN EQUILIBRIUM |
| 451 | JNC \$+6 | |
| 452 | MOV @R1,#01H | |
| 453 | JMP \$+4 | |
| 454 | MOV @R1,#00H | |
| 455 | MOV A,@R0 | |
| 456 | XRL A,R5 | |
| 457 | JZ EQCARR | |
| 458 | DEC R1 | |
| 459 | MOV A,R5 | |
| 460 | ADD A,#01H | |
| 461 | JNC \$+6 | |
| 462 | MOV @R1,#01H | |
| 463 | JMP \$+4 | |
| 464 | MOV @R1,#00H | |
| 465 | XRL A,@R0 | |
| 466 | JZ EQCARR | |
| 467 | MOV A,R5 | |
| 468 | CPL A | |
| 469 | ADD A,#01H | |
| 470 | CPL A | |
| 471 | MOV R7,A | |
| 472 | JNC \$+6 | |
| 473 | MOV @R1,#00H | |
| 474 | JMP \$+6 | |

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475      INC R1
476      MOV A,@R1
477      DEC R1
478      MOV @R1,A
479      MOV A,R7
480      XRL A,@R0
481      JZ EQCARR
482 UNSTAB:  MOV A,R5
483      MOV @R0,A
484      MOV R1,#7BH
485      INC R0
486      MOV A,#R1
487      MOV @R0,A
488      MOV A,#0FEH
489      MOV T,A
490      STRT CNT
491      SEL RB0
492      JMP RUN
493 EQCARR:  MOV R0,#7DH
494      MOV R1,#7AH
495      MOV A,@R0
496      XRL A,@R1
497      DEC R0
498      JNZ UNSTAB
499      MOV A,@R1      ;DATA ACCEPTED
500      CPL A
501      JB0 $+4
502      CPL F0
503      CLR C
504      MOV R0,#20H    ;CONVERT HEX TO BCD
505      MOV $7,#00H
506      MOV @R0,#00H
507 NSD:     MOV A,R5
508      CPL A
509      ADD A,#0AH
510      JC LSD
511      INC R7
512      CPL A
513      MOV R5,A
514      JMP NSD
515 LSD:     MOV A,R5
516      MOV R6,A
517 HUNS:    MOV A,R7
518      CPL A
519      ADD A,#0AH
520      JC ADD256
521      INC@R0
522      CPL A
523      MOV R7,A
524      JMP HUNS
525 ADD256:  JF0 $+4
526      JMP AVOUT
527      MOV A,R6
528      ADD A,#06H
529      MOV R6,A
530      MOVA,R7
531      ADD A,#05H
532      MOVR7,A
533      MOV A,@R0
534      ADD A,#02H
535      MOV @R0,A
536      MOV A,R6
537      ADD A,#0F6H
538      JNC $+5
539      INC R7
540      MOV R6,A
541      CLR C
542      MOV A,R7
543      ADD A,#0F6H
544      JNC $+5
545      MOV R7,A
546      INC @R0
547      CLR C
548 AVOUT:   SEL RB0
549      MOV A,R4
550      INC A
551      RL A
552      ADD A,R4
553      ADD A,#24H
554      MOV R1,A      ;STORE STRESS READING
555      MOV R0,#20H
556      MOV R7,#03H

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557      MOV A,@R0
558      MOV @R1,A
559      DEC R0
560      DEC R1
561      DJNZ R7,$-4
562      DJNZ R4,$+4
563      JMP GEL
564      JMP LOAD
565  RECALL: ANL P2,#0A0H
566          ORL P2,#02H
567          MOV A,#0FBH
568          MOV T,A
569          STRT CNT          ;START 5 SEC. TIMER
570          JTF $+9
571          IN A,P1
572          ANL A,#0FH
573          XRL A,#0AH
574          JNZ $+4
575          JMP KEYOUT
576          JNI $-11
577          IN A,P1          ;READ MEMORY LOCATION
578          ANL A,#0FH
579          MOV R4,A
580          RL A
581          ADD A,R4
582          MOV R4,A
583          ADD A,#21H
584          MOV R1,A
585          MOV R0,#1EH      ;LOAD STRESS DATA
586          MOV R7,#03H
587          MOV A,@R1
588          MOV @R0,A
589          INC R0
590          INC R1
591          DJNZ R7,$-4
592          MOV A,R4          ;CALCULATE RPM ADDRESS
593          ADD A,#40H
594          MOV R1,A
595          MOV R0,190 1BH
596          MOV R7,#03H
597          MOV A,@R1
598          MOV @R0,A
599          INC R0
600          INC R1
601          DJNZ R7,$-4
602          CALL DISP
603          CALL CLRFFIF
604          JMP RECALL
605  STORE:  IN A,P1
606          ANL A,#0FH
607          MOV R5,A
608          XRL A,#0AH
609          JNZ $+4
610          JMP KEYOUT
611          JNI STORE
612          MOV A,R5          ;CALC STRESS ADDRESS
613          RL A
614          ADD A,R5
615          MOV R4,A
616          ADD A,#23H
617          MOV R5,A          ;CALCULATE RPM ADDRESS
618          MOV A,R4
619          ADD A,#40H
620          MOV R4,A
621          CALL STODATE     ;STORE STRESS DATA
622          MOV A,R4
623          MOV R1,A
624          MOV R0,#1BH      ;STORE RPM DATA
625          MOV R3,#03H
626          MOV A,@R0
627          MOV @R1, A
628          INC R0
629          INC R1
630          DJNZ R3,$-4
631          CALL CLRFFIF     ;CLEAR FIFO OF 8279
632          JMP KEYOUT
633  KEYOUT: STOP TCNT
634          JTO $+4
635          JMP $+13
636          JFI $+9
637          CALL RPM
638          CALL STRESS

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639      CALL DISP
640      CPL F1
641      JMP KYBD
642      CLR F1
643      JMP KYBD
644      ORG 400H
645  OFFADJ:  MOV R0,#7FH
646          CLR A
647          MOV R3,A
648          MOV @R0,A
649          MOV A,#0FEH
650          MOV T,A
651          STRT CNT          ;START 2 SEC. TIMER
652          JTF $+4
653          JMP $-2
654          STOP TCNT
655  CAL:    ANL P2,#0A0H
656          ORL P2,#02H
657          IN A,P1
658          ANL A,#0FH
659          XRL A,@0AH
660          JNZ ADJUST
661          CALL STRESS
662          CALL DISP
663          JMP CAL
664  ADJUST: MOV A,#0FEH
665          MOV T,A
666          STRT CNT          ;START 2 SCE. TIMER
667          JIF $+4
668          JMP $-2
669          STOP TCNT
670          ANL P2,#0A0H
671          ORL P2,#04H
672          IN A,P1          ;READ OFFSET
673          MOV R2,A
674          ORL P2,#08H
675          IN A,P1
676          ANL A,#0FH
677          MOV R0,@7EH
678          MOV @R0,A
679          CALL COMP
680          JZ $+6
681          MOV A,R2
682          MOV R3,A
683          JMP ADJUST
684          MOV R1,#7FH
685          MOV A,@R0
686          JNZ $+6
687          MOV A,R2
688          MOV @R1,A
689          JMP $+6
690          MOV A,R2
691          ADD A,#80H
692          MOV @R1,A
693          CLR C
694          CLR F1
695          JMP KYBD
696  DISP:   PREP 0F0H, 15H,90H
697          ANL P2,#0EFH          ;SET C/D LOW
698          MOV R0,#1BH
699          MOV R2,#06H
700  EACH:   MOV A,@P0
701          ADD A,#TAB7
702          MOVP3 A,@A
703          OUTL BUS,A
704          INC R0
705          DJNZ R2,$+3
706          RETR
707          JMP EACH
708  STRESS: ANL P2,#0A0H
709          ORL P2,#04H
710          MOV R0,#20H
711          IN A,P1          ;READ LSD AND NSD
712          MOV R1,A
713          ORL P2,#08H          ;SET A9 HIGH
714          NOP
715          IN A,P1          ;READ MSD
716          ANL A,#0FH
717          MOV @R0,A
718          DEC R0
719          MOV A,R1
720          SWAP A

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725 ANL A,#0FH
726 MOV @R0,A ;LOAD DATA TO REGISTER
727 DEC R0
728 MOV A,R1
729 ANL A,#0FH
730 MOV @R0,A
731 CLR C
732 MOV R0,#20H
733 MOV $1,#03H
734 MOV A,@R0
735 ADD A,@0F5H
736 JNC 4+4
737 JMP STRESS
738 DEC R0
739 DJNZ R1,$-8
740 MOV R0,#7EH
741 MOV R1,#7FH
742 MOV A,@R1
743 MOV @R0,A
744 NEWOFF: MOV R0,#7EH
745 MOV A,@R0
746 MOV R1,A
747 JNZ $+4
748 JMP ADJOUT
749 JB7 NEGOFF
750 MOV R0,#20H
751 MOV A,@R0
752 XRL A,#0AH
753 JZ ADDN
754 MOV R0,#1EH
755 MOV A,@R0
756 JZ $+8
757 DEC A
758 MOV @R0,A
759 CNTR: DJNZ R1,$-7
760 JMP ADJOUT
761 INC R0
762 MOV A,@R0
763 JZ $+9
764 DEC A
765 MOV @R0,A
766 DEC R0
767 MOV @R0,#09H
768 JMP CNTR
769 MOV R0,#20H
770 MOV A,@R0
771 JZ $+12
772 DEC A
773 MOV @R0,A
774 DEC R0
775 MOV @R0,#09H
776 DEC R0
777 MOV @R0,#09H
778 JMP CNTR
779 MOV @R0,#0AH
780 JMP ADDN
781 NEGOFF: MOV R0,#2 0H
782 MOV A,@R0
783 XRL A,#0AH
784 JNZ CLRB7
785 MOV R0,#1EH
786 MOV A,@R0
787 DEC A
789 MOV @R0,A
790 ANL A,#0FH
791 MOV R1,A
792 DJNZ R1,$+4
793 JMP ADJOUT
794 MOV R0,#7EH
795 MOV A,@R0
796 DEC A
797 MOV @R0,A
798 MOV R0,#1EH
799 MOV A,@R0
800 JNZ $+6
801 MOV R0,#20H
802 MOV @R0,#00H
803 JMP NEWOFF
804 CLRB7: MOV A,R1
805 ANL A,#0FH
806 MOV R1,A
807 ADDN: MOV R0,#1EH

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|-----|---------|--------------|----------------------|
| 808 | | MOV A,@R0 | |
| 809 | | INC A | |
| 810 | | DA A | |
| 811 | | NOP | |
| 812 | | NOP | |
| 813 | | NOP | |
| 814 | | JB4 \$+9 | |
| 815 | | MOV @R0,A | |
| 816 | | DJNZ R1,\$+4 | |
| 817 | | JMP ADJOUT | |
| 818 | | JMP ADDN | |
| 819 | | ANL A,#0FH | |
| 820 | | MOV @R0,A | |
| 821 | | INC R0 | |
| 822 | | JMP \$-19 | |
| 823 | ADJOUT: | MOV R0,#1EH | |
| 824 | | MOV A,@R0 | |
| 825 | | JNZ \$+14 | |
| 826 | | INC R0 | |
| 827 | | MOV A,@R0 | |
| 828 | | JNZ \$+10 | |
| 829 | | INC R0 | |
| 830 | | MOV A,@R0 | |
| 831 | | XRL A,#0AH | |
| 832 | | JNZ \$+4 | |
| 833 | | MOV @R0,#00H | |
| 834 | | RETR | |
| 835 | RPM: | ANL P2,#0A0H | |
| 836 | | ORL P2,#01H | |
| 837 | | MOV R0,#1BH | |
| 838 | | MOV R7,#03H | |
| 839 | | MOV R1,#10H | ;SET MASK |
| 840 | RPMIN: | IN A,P1 | |
| 841 | | MOV R3,A | |
| 842 | | CPL A | |
| 843 | | ANL A,R1 | |
| 844 | | XRL A,R1 | |
| 845 | | JNZ RPMIN | |
| 846 | | MOV A,R3 | |
| 847 | | ANL A,#0FH | |
| 848 | | MOV @R0,A | |
| 849 | | INC R0 | |
| 850 | | DJNZ R7,\$+3 | |
| 851 | | RETR | |
| 852 | | MOV A,R1 | |
| 853 | | RL A | ;ROTATE MASK |
| 854 | | MOV R1,A | |
| 855 | | JMP RPMIN | |
| 856 | COMP: | CLR F1 | |
| 857 | | CLR C | |
| 858 | | MOV A,R2 | |
| 859 | | CPL A | |
| 860 | | ADD A,R3 | |
| 861 | | INC A | |
| 862 | | JNC LTEQ | |
| 863 | | CPL F1 | |
| 864 | | JN \$+3 | |
| 865 | | CLR F1 | |
| 866 | LTEQ: | RETR | |
| 867 | ENTER: | MOV A,#93H | |
| 868 | | OUTL P2,A | |
| 869 | | MOV R0,#18H | |
| 870 | | MOV A,@R0 | |
| 871 | | INC R0 | |
| 872 | | SWAP A | |
| 873 | | ADD A,@R0 | |
| 874 | | INC R0 | |
| 875 | | SWAP A | |
| 876 | | OUTL BUS,A | |
| 877 | | MOV A,@R0 | |
| 878 | | OUTL BUS,A | |
| 879 | | CLR A | |
| 880 | | MOV @R0,A | |
| 881 | | DEC R0 | |
| 882 | | MOV @R0,A | |
| 883 | | DEC R0 | |
| 884 | | MOV @R0,A | |
| 885 | | RETR | |
| 886 | MIX: | MOV A,#0F5H | |
| 887 | | MOV T,A | |
| 888 | | STRT CNT | ;START 10 SEC. TIMER |
| 889 | | MOV R0,#1AH | |

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890      MOV R6,#0DIH
891      MOV R3,#03H
892      MOV A,R6
893      MOVP3 A,@A
894      MOV @R0,A
895      DEC R0
896      INC R6
897      DJNZ R3,$-5
898      CALL ENTER
899      MOV R0,#1DH
900      IRP X, 9BH,11H
901      MOV @R0,#X
902      DEC R0
903      ENDM
908      MOV @R0,#12H
909      CALL DISP
910      MOV A,#82H
911      OUTL P2,A
912      JTF $+11
913      IN A,P1
914      ANL A,#0FH
915      XRL A,#0AH
916      JZ $+4
917      JMP $-9
918      STOP TCNT
919      RETR
920  STODAT:  MOV A,R5
921          MOV R1,A
922          MOV R0,#20H
923          MOV R3,#03H
924          MOV A@R0
925          MOV @R1,A
926          DEC R0
927          DEC R1
928          DJNZ R3,$-4
929          RETR
930  GMESS:  MOV R0,#20H          ;LOAD 'GEL' MESSAGE
931          IRP M, OEH,FH
932          MOV @R0,#M
933          DEC R0
934          ENDM
939          MOV @R0,#10H
940          RETR
941  AUMESS:  MOV R0,#20H          ;LOAD 'AU' MESSAGE
942          IRP M, OBH,OCH
943          MOV @R0,#M
944          DEC R0
945          ENDM
950          MOV @R0,#0DH
951          RETR
952  CLRFIG:  PREP 0F0H,15H,0C2H
953          RETR
958          ORG 3D1H
959          DB 07H,00H,00H,06H,00H,00H,03H,00H
960          DB 00H,02H,00H,00H,01H,00H,00H,00H
961          DB 06H,00H,00H,03H,00H,00H,01H,05H
962          DB 00H,00H,06H,3FH,06H,5BH,4FH,66H
963          DB 6DH,7DH,07H,7FH,6FH,40H,00H,77H
964          DB 1CH,3DH,79H,38H,76H,06H,50H
965          END

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Although the presently preferred embodiment of the present invention has been shown and discussed herein, it will be understood that many variations and alternate embodiments of the invention will be apparent to those skilled in the art. For example, other types of optical encoders other than the Gray code encoder may be used to indicate the angular position of the BOB. Furthermore, although the viscometer has been described as being used in connection with drilling fluids in the petroleum industry, it will be understood by those skilled in the art that the invention is applicable as well in measuring rheometric properties of any type of fluid.

What is claimed is:

1. A rotating-cylinder viscometer for measuring the shear stress at a given shear rate of a fluid contained between a rotatable outer cylinder and a rotatable inner cylinder, the inner cylinder rotating in response to

forces produced in the fluid by rotation of the outer cylinder, and where the amount of rotation of the inner cylinder is related to the shear stress of the fluid, the viscometer comprising:

- (a) a system clock, for providing system clock signals;
- (b) a microprocessor unit responsive to said system clock, for inputting and outputting data signals to select the shear rate of rotation of the outer cylinder and to obtain during measurement intervals a plurality of readings of the amount of angular rotation of the inner cylinder at each selected shear rate;
- (c) a shear rate controller responsive to said clock and the shear rate selecting data from said microprocessor, for rotating the outer cylinder at a predetermined constant angular velocity;

- (d) a position indicator connected to the inner cylinder for rotation therewith, for indicating the angular position of the inner cylinder;
- (e) a function selector means connected to said microprocessor, for inputting to said microprocessor the mode of operation for the viscometer, and for inputting the preselected shear rates at which the outer cylinder is to be rotated; and
- (f) display means responsive to said microprocessor, for displaying both a measured shear stress and the angular velocity of the outer cylinder at which the displayed shear stress was measured, said microprocessor determining from the average angular readings for the plurality of angular position readings of the inner cylinder for each measurement interval when the steady state shear stress has been reached, the steady state shear stress obtaining when the average angular readings for consecutive measurement intervals differ by no more than a predetermined amount.
2. The viscometer of claim 1 wherein the system clock is crystal controlled.
3. The viscometer of claim 1 wherein the shear rate controller comprises:
- (a) a motor, for rotating the outer cylinder;
- (b) a speed encoder connected to the outer cylinder for rotation therewith, said encoder outputting a feedback frequency signal;
- (c) a programmable frequency divider responsive to the shear rate selecting data, for dividing the feedback frequency signal to obtain a phase detector clock signal; and
- (d) a motor drive means responsive to the system clock and the phase detector clock signal, for generating the excitation signal to said motor, whereby the motor speed is controlled in accordance with the shear rate selecting data to obtain a constant frequency for the feedback frequency signal.
4. The viscometer of claim 3 wherein said speed encoder is an optical incremental encoder.
5. The viscometer of claim 3 wherein said motor drive means is enabled by said microprocessor to drive said motor, said means comprising:
- (a) a phase detector responsive to a system clock signal and the phase detector clock signal, for generating a phase error signal indicative of the phase between the phase detector clock signal and the clock signal; and
- (b) an amplifier, for generating the motor excitation signal from the phase error signal thereby causing said motor to rotate.
6. The viscometer of claim 3 wherein said motor is a DC-motor of the ironless armature type.
7. The viscometer of claim 3 wherein said programmable frequency divider is a divide-by-N counter.
8. The viscometer of claim 1 wherein said position indicator is an absolute value shaft encoder that outputs a code indicative of the absolute value of the shaft angle.
9. The viscometer of claim 8 wherein the code is a Gray code.
10. The viscometer of claim 9 further comprising a code converter for converting the Gray code to a BCD code.
11. The viscometer of claim 10 wherein said code converter is a read-only memory containing BCD code words that are outputted in response to memory ad-

resses provided by the Gray code output of said absolute value shaft encoder.

12. The viscometer of claims 1 or 8 wherein the predetermined amount of angular difference between the average angular readings of consecutive measurement intervals is $\pm 1^\circ$.

13. The viscometer of claim 1 wherein said function selector means comprises:

- (a) a keyboard having a plurality of keys including keys for generating numeric data, for generating digital code words in response to the actuation of the keys; and
- (b) an interface, for interfacing the digital code words to said microprocessor, said interface generating an interrupt strobe when a numeric key is depressed.

14. A method of obtaining the shear stress of a fluid at a selected shear rate speed using a rotating-cylinder viscometer having rotatable inner and outer concentric cylinders comprising the steps of:

- (a) mixing the fluid by rotating the outer cylinder at a high speed;
- (b) rotating the outer cylinder at the selected shear rate speed;
- (c) determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken at a predetermined sample rate, the angular position of the inner cylinder having random fluctuation about a position;
- (d) obtaining the difference between the current average value and the last obtained average value;
- (e) repeating steps (c) through (e) if the difference is greater than a predetermined number of degrees, the current average value becoming the last obtained average value for the next steady state determination; and
- (f) reporting the current average value as the measured shear stress if the difference is less than the predetermined number of degrees.

15. The method of claim 14 wherein the step of mixing the fluid occurs at a speed at least as high as the selected shear rate speed at which the shear stress is to be measured.

16. The method of claim 14 wherein the predetermined sample rate is at least twice the rate of the fluctuation in the angular position of the inner cylinder.

17. The method of claim 16 wherein the predetermined number of degrees is ± 1 degree.

18. The method of claim 14 further including the steps of:

- (a) determining the angular offset position of the inner cylinder at zero shear rate; and
- (b) correcting all angular position measurements of the inner cylinder by the amount of the zero rate offset.

19. A method of obtaining the steady state shear stress of a fluid at a selected shear rate speed using a rotating-cylinder viscometer in which the fluid is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder, the inner cylinder rotating in response to the torque produced by the rotation of the outer cylinder in the fluid whereby the angular rotation of the inner cylinder is indicative of the shear stress of the fluid; the method comprising the steps of:

- (a) mixing the fluid by rotating the outer cylinder at a speed at least as high as the selected shear rate speed at which the shear stress is to be measured for a first predetermined interval of time;

- (b) rotating the outer cylinder at the selected shear rate speed for a second predetermined interval of time;
- (c) determining a current average value for the angular position of the inner cylinder from a predetermined number of position measurements taken over a third predetermined time interval;
- (d) obtaining the difference between the current average value and the last obtained average value;
- (e) repeating steps (b) through (d) if the difference is greater than a predetermined number of degrees, the current average value becoming the last obtained average value for the next steady state determination; and
- (f) reporting the current average value as the measured shear stress if the difference is less than the predetermined number of degrees.

20. A method of obtaining the shear stress profile of a fluid for various preselected shear rate speeds using a rotating-cylinder viscometer having rotatable inner and outer concentric cylinder comprising the steps of:

- (a) mixing the fluid by rotating the outer cylinder at a high speed;
- (b) rotating the outer cylinder at a current shear rate speed;
- (c) determining a current average value for the angular position of the inner cylinder from a position measurements taken at a predetermined sample rate, the angular position of the inner cylinder having random fluctuations about a position;
- (d) obtaining the difference between the current average value and the last obtained average value, the current average value becoming the last obtained average value for the next difference determination;
- (e) repeating steps (c) through (d) if the difference is greater than a predetermined number of degrees;
- (f) storing the current average value as the measured shear stress if the difference is less than the predetermined number of degrees; and
- (g) repeating steps (c) through (f) until the shear stress at each of the preselected shear rate speeds has been measured thereby obtaining the shear stress profile of the fluid.

21. The method of claim 20 wherein the step of mixing the fluid occurs at a speed at least as high as the highest preselected shear rate speed at which the shear stress is to be measured.

22. The method of claim 20 wherein the predetermined sample rate is at least twice the rate of the fluctuations in the angular position of the inner cylinder.

23. The method of claim 20 wherein the predetermined number of degrees is ± 1 degree.

24. The method of claim 20 further including the steps of:

- (a) determining the angular offset position of the inner cylinder at zero shear rate; and
- (b) correcting all angular position measurements of the inner cylinder by the amount of the zero rate offset.

25. The method of claim 23 or 24 wherein the method further includes the steps of:

- (a) rotating the outer cylinder at 3 revolutions per minute;
- (b) measuring the maximum shear stress reading that occurs during one revolution of the outer cylinder;
- (c) repeating steps (a) and (b) after a predetermined time delay.

26. A method of obtaining a shear stress profile of a fluid for various preselected shear rate speeds using a rotating-cylinder viscometer in which the fluid is contained between a rotatable outer cylinder and a spring loaded rotatable inner cylinder, the inner cylinder rotating in response to the torque produced by the rotation of the outer cylinder in the fluid whereby the angular rotation of the inner cylinder is indicative of the shear stress of the fluid the method comprising the steps of:

- (a) mixing the fluid by rotating the outer cylinder at a speed at least as high as the highest shear rate speed at which a shear stress is to be measured for a first predetermined interval of time;
- (b) selecting one of the preselected shear rate speeds as the current shear rate;
- (c) rotating the outer cylinder at the current shear rate speed for a second predetermined interval of time;
- (d) determining a current average value for the angular position of the inner cylinder from position measurements taken at a predetermined sample rate over a third predetermined time interval, the angular position of the inner cylinder having random fluctuations about a position over a third predetermined time interval;
- (e) obtaining the difference between the current average value and the last obtained average value, the current average value becoming the last obtained average value for the next difference determination;
- (f) repeating steps (c) through (e) if the difference is greater than a predetermined number of degrees;
- (g) storing the current average value as the measured shear stress if the difference is less than the predetermined number of degrees; and
- (h) repeating steps (b) through (g) until the shear stress at each of the preselected shear rate speeds has been measured, thereby obtaining the shear stress profile of the fluid.

27. A microprocessor controlled rotating-cylinder viscometer for measuring the steady state shear stress of a fluid located between two coaxially aligned rotatable cylinders in which an outer cylinder is rotated at preselected rates and an inner cylinder is rotated from its zero rate position in response thereto, the viscometer comprising:

- (a) means for rotating the outer cylinder at a constant preselected rate;
- (b) a shaft encoder connected to the inner cylinder for encoding the angular position of the inner cylinder with respect to the zero rate reference position, the steady state angular position of the inner cylinder for a constant angular rate of the outer cylinder being indicative of the shear stress of the fluid located therebetween; and
- (c) a programmed microprocessor unit programmed to select the shear rate of rotation of the outer cylinder, and to repetitively obtain at each rate a plurality of readings of the angular position of the inner cylinder during measurement intervals, said processor unit determining the steady state shear stress from average readings of the plurality of angular positions of the inner cylinder determined for each measurement interval, the steady state shear stress obtaining when the average angular positions of the inner cylinder between successive measurement intervals differs by no more than a predetermined value.

28. The viscometer of claim 27 wherein the predetermined value of angular difference is $\pm 1^\circ$.

29. The viscometer of claim 27 wherein said shaft encoder is an absolute value shaft encoder for indicating the true angular position of the inner cylinder.

30. The viscometer of claim 27 wherein said rotating means comprises:

- (a) a motor responsive to a driving signal, for rotating the outer cylinder;
- (b) a speed encoder connected to the outer cylinder for rotation therewith, said encoder outputting a feedback frequency signal;
- (c) a programmable frequency divider responsive to the microprocessor, for dividing the feedback fre-

quency signal to obtain a phase detector clock signal;

(d) a phase detector responsive to said microprocessor and the phase detector signal, for generating a phase error signal indicative of the speed error between the selected shear rate and the actual rate of rotation of the outer cylinder; and

(e) an amplifier responsive to the phase error signal for generating the drive signal to said motor, whereby the motor speed is controlled in accordance with the selected shear rate from said microprocessor.

31. The viscometer of claim 30 wherein said speed encoder is an optical incremental encoder.

32. The viscometer of claims 30 or 31 wherein said motor is a DC-motor of the ironless armature type.

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